[redacted]

ELECTRONIC INSTRUMENTATION
FOR THE
BEHAVIORAL SCIENCES

Publication Number 320

AMERICAN LECTURE SERIES®

A Monograph in
The BANNERSTONE DIVISION *of*
AMERICAN LECTURES IN OBJECTIVE
PSYCHIATRY

Edited by

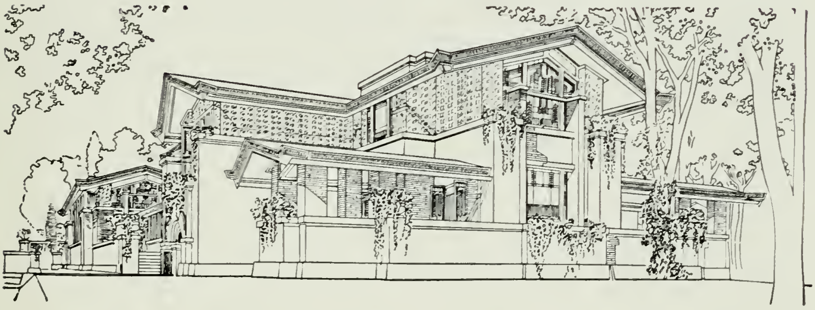
W. HORSLEY GANTT, M.D.
Phipps Psychiatric Clinic
The Johns Hopkins Hospital
Baltimore, Maryland

ELECTRONIC INSTRUMENTATION FOR THE BEHAVIORAL SCIENCES

By

CLINTON C. BROWN, Ph.D.
Chief, Psychophysiologic Research
Veterans Administration Hospital, Perry Point, Maryland

RAYFORD T. SAUCER, Ph.D.
Research Associate
Psychophysiologic Laboratory
Veterans Administration Hospital, Perry Point, Maryland



CHARLES C THOMAS • PUBLISHER
Springfield • Illinois • U.S.A.

CHARLES C THOMAS • PUBLISHER
BANNERSTONE HOUSE
301-327 East Lawrence Avenue, Springfield, Illinois, U.S.A.

Published simultaneously in the British Commonwealth of Nations by
BLACKWELL SCIENTIFIC PUBLICATIONS, LTD., OXFORD, ENGLAND

Published simultaneously in Canada by
THE RYERSON PRESS, TORONTO

Library of Congress Catalag Card Number: 57-12537

Printed in the United States of America

FOREWORD

W. Horsley Gantt

• • •

A knowledge of instruments is not only a keystone in research, but in our age, the complexity and diversity of instruments requires highly specialized knowledge of physics as well as biology. These authors are qualified in both respects. Dr. Clinton Brown has been one of my collaborators in psychopathological investigations of both patients and animals. The authors have a thorough understanding of the needs of research and a theoretical and also a practical knowledge of the necessary instruments. It is with great satisfaction that I have persuaded Dr. Clinton Brown to present the results of his experience with apparatus and instruments used in psychobiological research, a task in which he has solicited the useful collaboration of Dr. Saucer.

CONTENTS

LIST OF ILLUSTRATIONS

ELECTRONIC INSTRUMENTATION FOR THE BEHAVIORAL SCIENCES

Chapter 1

INSTRUMENTS AND BEHAVIOR

1.1. Some of the requisites for productive investigation in the behavioral sciences have undergone a drastic evolution in the last several decades. Fortunately, insight, skill and application are still the best of the primary tools of the researcher. Yet where it was once possible to begin an investigation with simple equipment (borrowed for the most part from classical physics), a speculative frame of mind and sound logic, it is now often necessary to expend a sizeable portion of research funds upon elaborate, costly and highly specialized equipment.

And this is not the total of expenditures, since it is most feasible to employ specialists to maintain and repair these research instruments.

Despite the advantages of increased sensitivity and accuracy of measurement provided by instrumentation, it may simetimes appear to the harassed investigator that his modern equipment represents a mixed blessing. This is particularly true since many researchers display basic prejudices against "gadgets," possibly based upon a lack of knowledge of the engineering principles involved.

Yet the need for complex instrumentation has arisen from a number of real sources.

First, much of the procedurally simple, pioneering type of investigation of more obvious behavior has already been performed. This does not imply that there are no new frontiers of investigation but only that there are relatively few basic contributions which can be made through the instrumentality of a Hipp chronoscope. Much needed information is of such a nature that it is more well hidden and subtle, inaccessible to such crude observation.

Second, fruitless research of the variety which yields unclear or uncertain data despite well-planned procedures have made the behavioral scientist increasingly aware of the necessity for exact and quantitative measures. It is perhaps redundant to state that this need is greatest in a field where the subject matter is so vaguely defined as it is in the area of human behavior. Decreasing the magnitude of observational errors is a means for defining more concisely the limits of complex phenomena. Post-experimental statistical manipulation is not an adequate solution to this problem. It is much more important to tap the phenomenon at its source. This is one of the exclusive advantages of good instrumentation.

It must be remembered that the instrument is a passive tool, and may not be considered as a substitute for good experimental ideas, careful planning and a thorough knowledge of the background of the problem. Yet the investigator who is ignorant of the possibilities afforded by instrumentation in behavioral research is unnecessarily handicapping his own efforts.

1.2. ***Research from Instruments.*** It has been the observation of the authors that the possession of a new type of research instrument leads often to the formulation of problems and hypothesis to be tested with this instrument. Observing the action of a new instrument, one may often spontaneously formulate a valuable problem in terms of "What if we did thus and so?" The instrument serves somewhat as a spur to the imagination or to crystallize a plan of approach to a particular segment of behavior.

The literature is full of evidence of the entirely dependant relationship of certain lines of investigation upon the development of the instrumental means for their investigation. Much of the work on audition awaited the development of the vacuum-tube oscillator, the whole area of EEG and related bio-electric phenomena depended greatly upon the development of suitable amplifiers and display devices, studies in basic neurology were not possible until suitable stimulating and recording devices were devised.

The ultimate fascinating possibility in instrumentation is that new circuits will be developed by physicists and engineers which will constitue an electrical analog of some hitherto unknown aspect of complex living behavior. The contemporary computing machines are veritable idiots by comparison with human reasoning abilities yet they may point the way to new and testable hypothesis in the fields of learning and memory.

Since work was begun on this manuscript, engineers have announced the development of the cryotron, an amplifying element similar to the transistor, yet so much smaller than the transistor that it compares favorably in size with a neural cell. While the principles of its operation may not presently be related to possible principles of neural conduction, such knowledge may stimulate a "breakthru" in basic neurophysiology.

1.3. ***Purpose of the Text.*** The materials to be presented in this text are directed towards a wide variety of specialists working in the general area of behavioral research; the experimental psychiatrist and psychologist, the psychophysiologist, physiologist, electroencephalographer, electrocardiographer, human engineer and the graduate students in these fields.

The material represents a summary of requisite background information and physical theory for the understanding of contemporary behavioral instrumentation together with an exposition of a wide variety of instruments for detecting and recording behavior. Emphasis has been placed on *how these instruments work,* their advantages and limitations, the minimum and optimum in instrumentation for specific problems. Much of a practical nature has been included such as suggestions on the design and construction of circuits, sources of supplies, relevant literature and periodical references.

Many of the circuits here presented have been designed by the authors and are presented as practical solutions to particular and frequent instrumentation problems. They may be constructed by the average technician from standard components.

Much new information has been presented, notably on the topic of transistors, input and output transducers, timing circuits and relay operation.

The reader with adequate physics or engineering background will probably omit Chapters II and III since they contain a brief summary of relevant theory. The individual with little or no engineering knowledge should read these chapters and some of the basic references listed in the bibliography which is appended.

Chapter 2

INTRODUCTION TO ELECTRONICS

2.1. ***Atomic Architecture.*** Only a brief introduction to the basic theory of electronics will be given here. The advanced student may omit this section while the beginning student may need additional reference reading in physics.

All matter is composed of molecules which are in turn made up of atoms. Each atom is made up of a fixed number of electrons rotating about a nucleus. The electrons possess a negative electrical charge, the nucleus has a predominately positive charge. Because like charges repel and unlike charges attract (just as the poles of a magnet), the orbital electrons are held into position in an arrangement resembling a concentric series of shells of ever-increasing diameters. The maximum number of electrons in each complete shell is fixed for a given element. The outermost shell is usually incomplete, containing gaps which may be filled by migrant electrons or surplus electrons which are free to move to other atoms. The handing on of migrant electrons from one adjacent atom to another is the essential process in electrical conduction.

Materials differ greatly in their electrical conductivity. The best conductors contain the greatest numbers of surplus electrons in their incomplete outer rings. Copper, which is an excellent conductor contains eleven electrons and seven gaps in its fourth and outer shell. It is this relatively large number of available electrons which makes copper conduct an electrical current so well. At the other end of the scale are materials like glass, mica and air which offer enormous resistance to the flow of electrons. These materials are good insulators.

Electrons always flow from and to a source. In the simplest electrical circuit (literally a "circle") composed of a battery with a wire connecting its two terminals, electrons are injected by the source, free electrons drift down the wire, displacing others and eventually return to the source. The rate of this motion may be only a few centimeters per second in metallic conductors to rates as rapid as 10^8 cm/sec in a vacuum.

2.2. ***Basic Electrical Units.*** The rate at which electrons flow in a conductor is termed "current" and the unit of measure is the "ampere." Amperes of electrical current flow is analogous to gallons of water per second flowing thru a pipe.

A battery or other source of electrical potential separates positive and negative charges which subsequently exert force in reuniting to form a neutral state. This force is called "electromotive force" which is abbreviated EMF and is expressed in units of volts. The higher the voltage in an electrical circuit the more readily it will drive a current thru a wire. Voltage is analogous to the pressure of water in a pipe.

Since an electron can move only one millionth of a centimeter before colliding with other particles or entering an orbit of an atom of the conducting substance, not all electrons complete the circuit. This opposition to the flow of current is termed "resistance" and is expressed in ohms. Electrical resistance is analogous to the resistance offered by small pipes to the flow of water.

These three basic characteristics of electrical energy; current, potential and resistance, bear a definite relationship to one another which is expressed in Ohms Law. Where E represents the voltage, I the current and R the resistance, Ohms Law may be expressed in three ways; E = RI, R = E/I and I = E/R. This is a very important, useful and absolutely basic law of all electronic circuitry.

Because of the inherent resistance to current flow of even the best conductors, the stoppages and collisions of electrons produce heat. This energy dissipated in heat is lost as far as electrical purposes are concerned. This is a loss of power, defined as the rate of doing work. Power is expressed in "watts" and is determined by the formula; P = EI.

2.3. ***Fractional Electrical Units.*** The ohm, watt, henry, ampere, volt are representative of relatively enormous amounts of energy. In most electronic applications, it will be found that decimal fractions of these basic units may be conveniently employed. At least one of these is most conveniently expressed as multiples of the unit value, such as in the case of resistance. Consequently, there are commonly used prefixes which denote fractional or multiple values. The most frequently used fractional designations are; "milli-," "micro-" and "micro-micro," denoting respectively, thousandths, millionths, and millionths of millionths of the unitary value. Multiples are denoted by the prefixes; "kilo-," "meg (a)-," and "meg(a)-meg(a)," denoting respectively, multiples of thousands, millions and million-millions. Transformations from one fraction or multiple to another are easily accomplished by shifting the decimal point in the proper direction.

2.4. ***Capacitance.*** If two conductors are placed in close proximity and each is connected to a source of EMF, it will be found that there is no current flow thru this junction due to the extremely high resistance afforded by the air or insulator separating them. If the source is disconnected and a suitable meter placed across these electrodes, it will be found that a charge remains, equal and opposite in polarity to the impressed EMF. This property of a conductor-insulator-conductor assembly is known as "capacitance" and the assembly is called a "capacitor" or "condenser." The quantitative expression of capacity is that of the "farad" and the useful units are usually small fractions of a farad. Capacitance may be increased by using larger electrodes, bringing them closer together, or changing the insulator separating the electrodes. This is represented in the equation for capacitance:

$$C = 0.224 \frac{KA}{d} (n\text{-}1) \qquad \textit{Equation 2.1}$$

where K is the dielectric constant for the insulator, A is the area of the electrode, and d is the distance between the electrodes. It is important to remember that *steady* potentials do not flow thru a condenser.

Reviewing, it is now apparent that electrons may be made to flow from a source, thru a conductor, and back to the source creating a flow of energy. This flow has two important characteristics, potential and current which may be measured and expressed in volts and amperes. Electrical flow always meets some degree of resistance which may be expressed in ohms with subsequent loss of power in the form of heat. The power may be expressed in terms of watts.

2.5. ***Direct and Alternating Currents.*** To this point the discussion has assumed a unidirectional flow of current from and to the source. This is termed "direct current" and is abbreviated DC. DC potentials are usually those created by a battery which because of chemical action has an electron rich terminal (negative) and an electron deficient terminal (positive). The direction of current flow is therefore from negative to positive terminals.

There is another type of current flow termed "alternating current" and abbreviated AC. It is also accomplished by electron migration but there is one important difference, the source is constantly changing polarity and the flow of current consequently rises to a maximum in one direction, falls to zero, rises to a maximum in the other direction, falls to zero, and so on. Two more terms descriptive of AC current flow must be added; frequency and waveform. Frequency may be defined as the number of reversals per unit time, usually a second. The waveform is best described graphically and represents the rate of change in potential. The most frequent waveform encountered in instrumentation work is the sine wave, representing a uniform rate of change. Waveforms may assume an infinite number of shapes, however.

There are many differences and similarities between the properties of AC and DC potentials. One of the most important of these is the measurement of the absolute magnitude of the potential. In DC, it is simply that which is measured. In AC, the value depends upon the time at which the measure is made, since it is constantly changing. The EMF of AC is therefore expressed in one of two ways; as "peak-to-peak" or "RMS" values.

The peak-to-peak value is simply the magnitude measured from trough to crest of the wave. The RMS value is equal to the square root of the mean of the instantaneous current values, the quantity squared. It is equal to approximately 70% of the peak-to-peak value.

Current flow in AC circuits is expressed in amperes or fractions but the concept of resistance discussed in connection with DC must be supplemented with a new concept of impedance, to be discussed later.

Perhaps the most striking peculiarity of AC is related to the dispersion of migrating electrons in a conductor. With DC, they are dispersed uniformly. With AC, the dispersion is uniform for low frequencies only. With increasing frequency, there is an increasing concentration of electrons towards the exterior of the conductor. Current propagation ultimately becomes external to the conductor and in electrical and magnetic forms travel vast distances as radio signals.

2.6. *Electromagnetism and Inductance.* If an iron bar is wound about with a length of wire and the two ends connected to a battery, the bar will exhibit magnetic properties as long as the current flows. The intensity of the magnetism is approximately equal to the current flow thru the coil and whichever end assumes the property of North or South poles will depend upon the direction of current flow.

Special steels may be made permanently magnetic. If a coil of wire is connected to a sensitive meter and the magnet is moved quickly thru the coil a transient current flow will be noted. This current has been generated in the wire. It is not important whether the magnet or the wire is moved since the EMF is generated by the wires being cut by the lines of magnetic force.

If two coils are wound about the same steel core and one coil is connected to an AC source while the other is connected to a meter, it will be found that a current appears in the second coil when the first is energized. The principle is the same except that now both the coils and the core are stationary while the magnetic field intensity builds up and collapses thru both. It will also be found that for any particular instantaneous polarity of the first (primary) coil, the second coil (secondary) is exactly opposite.

This configuration of two or more coils wound on a common core is called a "transformer." The relationship of the applied to induced potentials is almost exactly that of the ratio of primary to secondary turns. The transformer therefore provides a means for "stepping up" or down an AC potential. The application of a DC potential creates transient induced potentials only at the "make" and "break" of the primary circuit since this is the only time when the magnetic field is in motion. Direct current is therefore not passed by a transformer.

2.7. ***Inductance.*** If an AC potential is applied to a transformer and a constant measurement made of the magnetism of the core, it will be noted that the instant of greatest magnetism and that of the peak impressed voltage are not simultaneous. Peak magnetism will lag peak impressed voltage by exactly one quarter of a cycle, also expressed as 90 electrical degrees. This is due to the fact that the initial flow of current produces magnetic lines of force which move thru the coil and induce an EMF which is opposite to that applied. This "bucks" the initial current flow. When the full current flow is established and begins to decline, lines of force again move thru the coil and again induce an EMF opposite to that applied. In the first instance, the induced EMF caused a lag in peak magnetism, in the latter, the induced EMF caused a prolongation of the magnetic effect. Inductance therefore provides a kind of flywheel effect, introducing temporal inertia in the circuit. This effect will be discussed at greater length beneath.

2.8. ***Impedance.*** While the voltages in the primary and secondary windings of a transformer are in proportion to the ratio of their turns, there is no power gain. Consider a resistor R connected across the secondary so that a current I flows. The power absorbed in the secondary is equal to E_s x I_s, and that absorbed by the primary is equal to E_p x I_p, so that E_s x I_s = E_p x I_p. Therefore, E_p/E_s will equal I_s/I_p so that the relationship between voltage and current in a transformer is reciprocal. If the primary to secondary turns ratio is such that the voltage is stepped up, the current will be reduced, etc.

The generic term for the property of any component of an electrical circuit which suppresses or opposes current flow is "impedance." Simple DC resistance discussed in 2.2 is an example of this. Coils and transformers, by virtue of the resistance of the wire of which they are made also show simple DC resistance. With AC potentials, inductors show another type of impedance to current flow which may be termed "inductive reactance." It depends upon the complex reaction of current flow and electrical magnetism described in *2.7* above.

The actual calculation of the reactance of an inductor involves the consideration of the frequency of the applied AC. Reflection will show that this is an important factor, since an inductor characteristically causes the current to lag behind the voltage and the amount of this lag is proportionally greater at higher frequencies. The value of reactance may be calculated from the formula: X = 2 pi f L ohms; where L is the inductance in henries and f is equal to the frequency in cycles per second.

The final consideration in calculating the impedance of multi-coil inductors such as transformers, is that of the impedance of the circuit connected to the secondary coil.

The value of this impedance will be "reflected" into the existing impedance of the primary. The reason for this is as follows: Consider a load resistor R, connected to the secondary coil of a transformer. The secondary then draws a current equal to E_s/I_s from Ohms law. The primary winding now appears as if it had a kind of resistance, R_p, equal to E_p/I_p associated with it. This reflected or virtual impedance is related to R_s and varies with it in the ratio of the square of the turns ratio of the transformer. For example, in a transformer with a turns ratio of 10:1, a load resistor of 100 ohms will produce a reflected impedance of 10,000 ohms in the primary.

The AC impedance of an inductor does not represent the same kind of power loss as does the factor of resistance in a DC circuit. Instead, it represents a storage of energy.

2.9. ***Capacative Reactance.*** The basic properties of a capacitor discussed above included that of the storage of a quantity of electricity. It is now important to examine briefly the manner in which this charge is stored, since it will be seen that the condenser also impedes current flow.

At the moment that an EMF is impressed across an uncharged capacitor, a large current begins to flow. As it does so, the voltage across the capacitor rises and, since it is opposite in polarity to the impressed voltage, it begins to oppose the flow of the charging current. The longer the condenser is charging, the greater is the opposite charge on the condenser and therefore the slower additional charge is accepted. Eventually the system reaches equilibrium at the full value of the impressed EMF. A continuous plot of these values would show that the current flow in the circuit is large at first and declines exponentially with time until full charge is reached.

When this fully charged condenser is discharged thru a resistor, the reverse of the above process takes place. At the first instant of discharge the current flow is great, but as the condenser charge is drained off, the magnitude of the potential remaining to drive a current thru the resistor is reduced and the flow thru the resistor is lessened. The net effect is that of an exponential decay of the charge on the condenser.

The *slope* of the curve of charge or discharge is dependant upon the product of two circuit factors; resistance and capacitance. Their product is called the RC product and is discussed more completely in Chapter VII.

While DC cannot flow *thru* a condenser, alternating current may appear to do so. This is due to the fact that the charge which is built up on one half of the AC cycle is dissipated during the declining portion of that cycle in a repetitive fashion. The condenser action is therefore that of "smoothing" an impressed AC potential.

The impedance presented by a condenser is termed "capacitative reactance" and its value is dependant upon the frequency of the AC impressed. Capacitative reactance may be calculated from the formula; $X = \frac{1}{2\pi fC}$ where C is in farads and f is the frequency in cycles per second. A condenser therefore, exhibits less impedance to high frequencies of AC than to low frequencies.

2.10. *Summary of Impedance.* Three different types of components discussed to this point possess the common characteristic of opposition to current flow; the resistor, capacitor and inductor. The impedance of each may be measured in ohms. The resistor offers the same amount of impedance to both AC and DC, irrespective of the frequency of the former. The impedance of an inductance is partly determined by its absolute value of inductance but also by the frequency of the impressed potential. It is minimum at DC and rises with increasing frequencies of AC. The impedance of a capacitor is nearly infinite at DC but decreases with increasing values of AC.

2.11. ***Load Match and Power Transfer.*** The internal impedance of a generator of EMF is always some finite value. It may be very low in the case of batteries or it may be in the order of kilohms in the case of living tissue, such as the cortex, which generates EMF. If this EMF is to be used efficiently, care must be taken to maintain certain relationships between the impedance of the source and that of the circuitry attached to it. This is a particularly important consideration in the use of electronic circuitry to amplify and record the electrical responses of living tissue.

Any source or generator of EMF may be considered as an ideal, zero-resistance source E, in series with its own internal resistance r. Under no-load conditions, the total output E will appear across the output. If any resistance R is connected to the source, a current will flow and the voltage E will be dropped across both R and r. The resultant effective EMF will depend upon the ratio of internal to external resistances:

$$E_{eff} = \frac{R}{R + r} \qquad \textit{Equation 2.2}$$

It is apparent that the optimum situation is that when these resistances are equal and 50% of the power is transmitted.

2.12. ***Circuit Algebra.*** Resistors, condensers and inductors may be connected in series or parallel arrangements as shown in Figure 2.1.

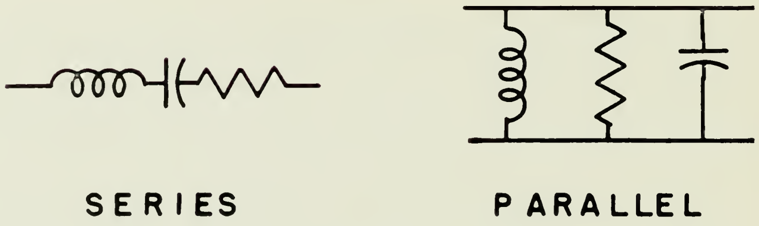


Fig. 2.1

The total values of these configurations may be found by the use of the formulae:

$$R_{tot}\text{ (Parallel)} = \frac{1}{1/R_1 + 1/R_2 + 1/R_n}$$

$$\text{and } R_{tot}\text{ (Series)} = R_1 + R_2 + R_n$$

$$\text{or } C_{tot}\text{ (Parallel)} = C_1 + C_2 + C_n$$

$$\text{and } C_{tot}\text{ (Series)} = \frac{1}{1/C_1 + 1/C_2 + 1/C_n}$$

As a general rule, it is easiest to begin with the simplest series and parallel combinations in more complex circuits, work out their value, then move on to the next most complex arrangement.

2.13. ***Voltage Dividers.*** When two resistors are connected in series across a source of potential, their total resistance is equal to the sum of their resistances. Since the same current flows thru each, it is apparent from Ohm's law that each resistor bears the same proportion of the total voltage as its resistance is to the total resistance. If E is the voltage impressed across series resistors R_1 and R_2, then the voltage e across resistor R_1 is equal to:

$$e = E\,\frac{R_1}{R_1 + R_2} \qquad \textit{Equation 2.3}$$

A potentiometer is a common electronic component made up of a circular resistor element with connections at each end, and a metallic "wiper" which may be rotated from one end terminal to the other. If the two ends of the potentiometer are connected across a source of EMF the voltage appearing between the wiper and either end may be varied from zero to the full value by rotating the wiper. The principle is the same as that described in the preceding paragraph. Whether made up of variable or fixed resistors, the principle of the voltage divider is basic in instrumentation circuitry since it permits the instrument to be operated from a single power source.

Chapter 3

VACUUM TUBES

3.1. ***Electron Flow in a Vacuum.*** The heart of modern electronic equipment is the vacuum tube and its solid state counterpart, the transistor. Transistors are discussed in Chapter 11. In instrumentation terminology "electronic" refers to devices using these components in contrast to electrical or mechanical devices. The smallest vacuum tubes are little larger than a pencil eraser, while some of the largest tubes may stand several feet high, but in all cases their applicability to instrumentation is based upon a) their ability to convert alternating current to direct current or direct current into alternating current and b) their ability to amplify voltage changes.

The operation of the thermionic tube or valve depends upon the free flow of electrons in an evacuated space. These free electrons are released from several substances by a variety of means, the most important being thermionic or heat emission.

3.2. ***Thermionic Emission.*** In metals or metallic oxides as well as in some gases the electrons in the outer orbits of the atoms may be loosely bound. Current will flow when a potential is applied to an aggregate of atoms, causing displacement of the electrons. In all metals which are at temperatures above absolute zero there is some random movement of electrons, but when substances are heated the electrons may leave the surface as though they were boiled off. In a vacuum these electrons will form a space charge around the emitter. The negative charge will then repel electrons and keep them from escaping from the surface. If a positively charged electrode is introduced into the vacuum the electrons will move to the positive electrode. Current then flows through the vacuum. This is the Edison Effect, discovered by Thomas Edison in the course of his work with incandescent bulbs.

3.3. ***Filaments.*** The heating element of a thermionic tube is called the filament. The heated element itself may be used as an emitter in battery tubes or in transmitting tubes, but more often the emitting element is a cylinder coated with metallic or rare earth oxides which emit electrons at a lower temperature than pure metals. This cylinder is called the cathode.

3.4. ***Filament Voltages.*** The current and voltage required to heat the cathode may vary from tube to tube. There is no standard nomenclature which will indicate the heater voltage, although the first number in a tube type may do so. For example, a 6SN7 tube requires 6.3 volts to heat the cathode, while a 12AU7 requires 12.6 volts. Receiver tube manufacturers provide handbooks at nominal cost which list the various operating voltages for standard tube types. (It may be mentioned at this point that any circuit work with vacuum tubes will require the reader to acquire one of these handbooks. Either the RCA or Sylvania manuals are entirely adequate.)

Filaments may be connected to the supply voltage in parallel if they have the same heater voltage rating. Thus, one finds that a multitube commercial instrument may have all 6.3 volt tubes. Tubes may be connected with the filaments in series if a) their current ratings are the same and b) the voltage ratings add up to the supply voltage. If the current ratings are unequal, shunt resistances must be provided. If the voltage ratings do not add up to the supply voltage series dropping resistances must be added.

3.5. ***Diode Tubes.*** The simplest vacuum tube is the diode or two element tube. It has a cathode and an anode, usually called the plate. Polarizing potentials called plate voltages are applied between the plate and the cathode. Current will then flow from cathode to anode but not from anode to cathode. The diode acts as a one-way valve for electron flow. If the polarizing potential is AC, current will flow only when the anode is positive with respect to the cathode. The output of the tube will be rectified pulsating DC. A schematic diagram of a diode tube is shown in Figure 3.1-A.

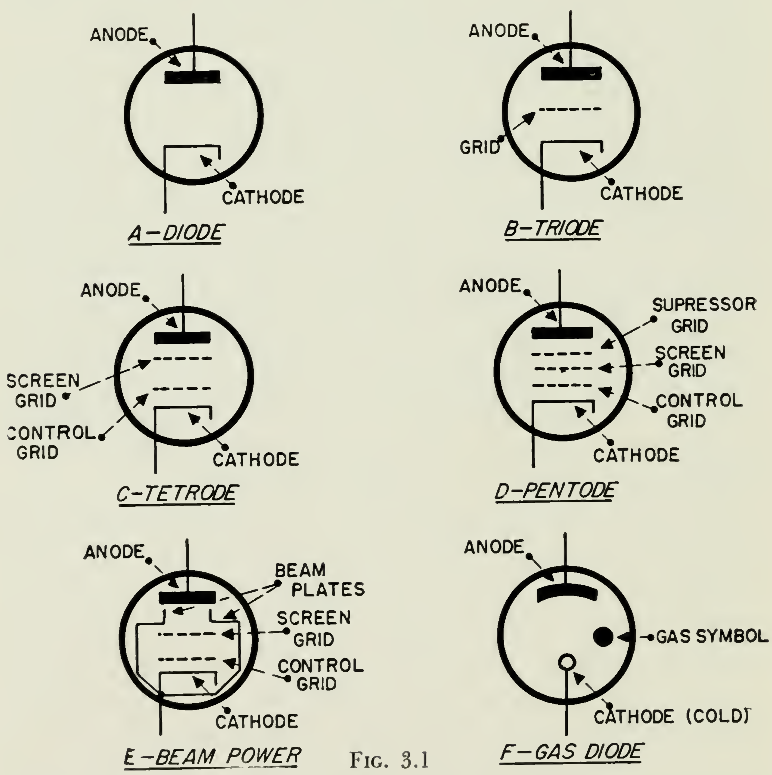


Fig. 3.1

3.6. ***Triode Tubes.*** The second type of tube is the three element tube or triode, as it is more commonly called. It is shown in Figure 3.1-B. DeForest is considered to be the inventor of the triode. He developed this tube from the diode by adding an additional element called the grid. The grid is a wire structure interposed between the cathode and the plate. When the grid is more negative than the cathode it repels electrons and exerts an electrostatic force which tends to concentrate the electrons in the vicinity of the cathode, where they add to the cathode space charge and retard the flow of current. The current flow in a triode is proportional to the relationship between the grid potential and the cathode potential. This difference is called the bias voltage. If the bias is very large, electron flow will cease. This point is called the cut-off voltage. If the grid becomes positive with respect to the cathode, the grid structure then becomes an anode and grid current flows. Linear operation of the tube lies somewhere between these points. At this point small changes in the grid voltage will produce large changes in the plate current.

Amplification is achieved by placing a resistive element or resistor called the load resistor in series with the plate. When an alternating voltage is applied to the grid, larger voltage changes will be developed across the load resistor. The output of the tube is taken between the junction of the plate and the load resistor and ground.

3.7. ***Amplification Factor.*** The ratio of the change in plate voltage for a unit change in the plate current compared to the change in the grid voltage required for unit change in plate current is called the amplification factor or mu (M) of the tube. The mathematical expression of mu is

$$M = \frac{\triangle ep}{\triangle eg}$$ *Formula 3.1*

given in Formula 3.1. In triode tubes, mu may very from about 3 to over 100. For any given tube the value of mu will be found in the tube manual.

3.8. ***Plate Resistance.*** The ratio of a small change in plate voltage to the plate current it produces when the grid voltage is fixed is called the plate resistance of the tube. It is also called the dynamic or AC resistance of the tube. The mathematical expression is given in Formula

$$R_p = \frac{\triangle ep}{\triangle ip} \qquad \textit{Formula 3.2}$$

3.2. It is an important characteristic because the tube and the load resistor appear as a voltage divider with the output taken from the junction. The larger the plate resistor the smaller the ratio and hence the greater the gain of the stage.

3.9. ***Transconductance.*** One of the most important tube parameters is the transconductance, represented by gm. Transconductance is the relationship between plate current and grid voltage changes. It is given

$$gm = \frac{\triangle ip}{\triangle eg} \qquad \textit{Formula 3.3}$$

in Formula 3.3. The unit of transconductance is the mho, which is ohm spelled backward. All of these parameters are related by mu = gm R_p.

3.10. ***Bias Voltage.*** The steady or quiescent current which a tube draws can be regulated by the bias. This may be necessary to insure linearity or to insure safe operation of the tube. If the tube is used as an AC amplifier the AC signal is superimposed on the bias voltage. For example, if a signal having a value of 3 volts peak to peak is applied to the input of tube having a 3 volt bias the voltage on the grid will swing 1.5 volts about the —3 volt center or bias. The maximum positive swing will be to —1.5 volts and the maximum negative swing will be to —4.5 volts. Since it does not go positive, no grid current will be drawn. If the sum of the bias and the signal voltages should exceed either the zero point or the cutoff point, distortion and non-linear operation will occur.

Bias voltages may be from a fixed source such as a bias battery or negative rectifier, from a gridleak arrangement or from the drop across a cathode resistor.

3.11. ***Fixed Bias.*** Batteries are seldom used nowadays for vacuum tube bias supply, although they may be found in transistor circuits. In instrumentation work the use of large negative potentials allows the designer to balance out DC potentials or to insert DC voltages in an output. Such bias potentials are usually furnished by a negative rectifier associated with the power supply. The use of 150 volt or 300 volt bias is apt to be confusing when these bias voltages are compared with tube handbook bias values. In most cases, however, if the actual grid to cathode potential is measured, the bias on the tube will be found to be in keeping with the handbook values.

3.12. ***Gridleak Bias.*** This type of bias is ordinarily found in radio frequency detector circuits or in oscillator circuits. If we consider that on positive swings the grid structure acts as an anode and that the grid will draw current, it can be seen that the positive cycles will be effectively shunted to ground by the grid and cathode. The negative peaks will charge the grid blocking condenser if the RC time constant is long compared to the negative part of the cycle. The presence of a negative potential when measured from grid to ground indicates that some grid current is being drawn. While this is proper in oscillator circuits, it is a sign of distortion in AC amplifier circuits in most cases.

3.13. ***Cathode Bias.*** This type of bias is developed by returning the grid resistor to ground and inserting a resistor in the cathode circuit. The drop across this resistor causes the cathode to rise above ground potential and hence above the grid potential, making the grid negative with respect to the cathode. A discussion of this method is in the RCA handbook and should be studied in detail, although it will be further discussed in 3.14. It is the most common method of providing bias for the proper operation of vacuum tubes. It has the additional advantage of adjusting the bias to the plate current flow, since the drop across the cathode resistor is proportional to the plate current flow.

3.14. ***Load Lines and Load Resistors.*** In order to design a triode circuit to have specific voltage output, current and load values and to operate within allowed limits, one must refer to the transfer characteristics. These characteristics are in the form of charts and can be found in the handbook or ordered in pads of 20 of one type from several supply houses. A sample chart including a circuit is given in Figure 3.2.

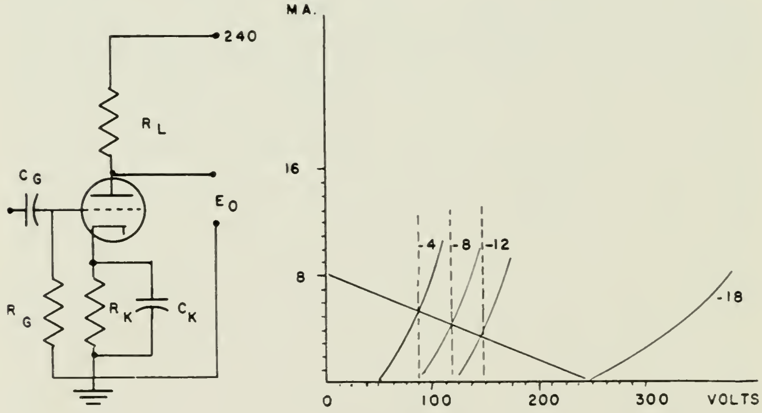


Fig. 3.2

The straight line drawn across the curves is called the load line. It is drawn from the supply voltage used (240) to the point where the current is limited by Ohm's Law. The plate voltage will be zero at this point. The slope of the line corresponds to the value of the load resistor. With a 30K load resistor the line goes from $I_p = 0$ to $I_p = 240/30K$ or 8 milliamperes.

The triode has a fixed bias of –8 volts. The operating point is the point at which the –8 volt bias curve crosses the load line. A line drawn to the I_p scale will give the quiescent plate current, which is about 4 milliamperes. If a signal having a peak to peak value of 8 volts is applied, the operating point will swing from –4 to –12 volts. A line drawn downward to the E_p scale will show that the voltage falls to about 87 volts. A line drawn from a –12 volt bias point will show that the voltage rises to about 142 volts. The difference will be about 55 or 56 volts for an 8 volt signal swing. The gain of the tube in this circuit is thus 56/8 or a factor of 7, which is representative of the gain to be obtained from a medium mu triode with a low value of load resistor.

If cathode bias is desired, the plate current is known to be 4 milliamperes. To fix the bias at –8 volts will require a cathode dropping resistor of 2,000 ohms. If this resistor is less than 10% of the plate load resistor, the additional series resistance can be ignored. If the tube is to be used as an AC amplifier, a cathode bypass condenser must be included. This is a large condenser which effectively shunts the cathode resistor for AC signals in such a way that there is no degenerative feedback.

Although the discussion has been applied to triode tubes, the same principles apply to the design of tetrode and pentode amplifiers.

3.15. *Tetrode Tubes.* The three elements in a triode tube form an electrostatic system with each element acting as the plate of a very small condenser. The actual capacity of each pair of electrodes may be very small, but in triode tubes the grid to plate capacity is multiplied by the gain of the stage. This is the Miller effect. Under these conditions the grid may be imperfectly isolated from the plate. The high frequency response of the tube may suffer or the stage may oscillate due to unwanted plate to grid coupling.

A schematic of a tetrode tube is shown in Figure 3.1-C. An additional grid called the screen grid is placed between the control grid and the plate. When operated at a positive potential this grid effectively lowers the grid to plate capacitance. It also makes the plate current nearly independent of the plate voltage. The transfer curves for a tetrode tube illustrate this. The tetrode tube is not commonly used for voltage amplifiers due to the superior performance of the pentode.

3.16. *Pentode Tubes.* When electrons accelerated by voltages over 20-25 volts fall on a metal surface they liberate electrons. This is known as secondary emission. In the tetrodes the screen grid is positive and will attract these electrons, causing plate to screen grid interaction. A fifth element is added in the pentode tube and is shown in Figure 3.1-D.

This element, known as the supressor or supressor grid is placed between the plate and the screen grid. It tends to return secondary emission to the plate. While this adds to the noise contributed by the tube, it effectively supresses secondary emission. The pentode has a low input capacitance, high gm and will give voltage gains up to 250 in a stable circuit.

3.17. ***Beam Power Tubes.*** A beam power tube is a tetrode with beam forming plates operated at cathode potential. These serve as virtual supressor grids and also to focus the electron stream into a beam. The beam can be modulated by relatively small grid voltages. The beam power tube is shown in Figure 3.1-D. These tubes are also called power output tubes. They are needed to drive devices such as speakers or writing transducers because they are capable of supplying more power than conventional voltage amplifiers.

3.18. ***Gas Diodes.*** Gases are composed of free atoms in random movement. The work function of a gas is characterized by the fact that few electrons are displaced until the polarizing voltage reaches a fixed value. At this point the gas becomes ionized. Ions move in one direction while electrons move in the other. The current will flow as long as the external resistance in the circuit is fairly low and will cause a fixed voltage drop across the tube which is less than the ionizing voltage. The schematic is shown in Figure 3.1-F. Gas diodes such as the VR-150 are used to regulate current and voltage, while others are used to regulate voltage only and serve as voltage reference points.

3.19. ***Thyratrons.*** The thyratron is also a gas filled tube but has a heated cathode. Its internal geometry is such that there is a narrow aperture from the cathode to the plate. A negative grid can hold the flow of electrons at cutoff for a given voltage applied to the plate. If, however, electron flow begins, the grid is surrounded by a sheath of ions and cannot regain control. The thyratron will act as a relay. It can pass substantial amounts of current, but the plate voltage must be interrupted before it can be biased again. It is shown in Figure 3.1-G. Since the voltage drop across a thyratron is perhaps 6-10 volts, they cannot be operated without some limiting resistance in the plate circuit.

Thyratrons may also be used with AC plate supplies. Under this condition of operation they will conduct as long as the grid is held positive. When the grid is allowed to go negative they will cut off, since the negative swing on the AC supply will effectively interrupt the plate voltage.

3.20. ***Photoelectric Emission.*** When any high velocity particles impinge upon a metal surface, secondary emission may occur if the work function (the binding force which holds electrons in the outer orbit that can be overcome by an amount of energy specific to a given metal) is low. Metals with a very low work function will release electrons when bombarded by light particles. This is known as photoemission. When a diode with a photoemissive cathode is polarized, a current which is proportional to the amount of light on the cathode will flow. Tubes of this type are known as photocells. They may be vacuum tubes, although some types contain a small amount of gas. They are very useful for measuring both relative and absolute light intensities.

3.21. ***Multipurpose Tubes.*** In order to save space and in some cases to conserve filament power some tubes are constructed with two or more diode, triode or pentode units in one envelope. Twin diodes and twin triodes are quite common. Many triode-pentode tubes are now appearing. Although they are usually designed to operate in TV circuits, they lend themselves to instrumentation work. It has been our experience that we need not stock single triode types, since the total cost of a twin triode is the same as that of a single tube.

3.22. *Low Potential Tubes.* Although they are too new to evaluate, tubes designed to operate with plate potentials as low as 12 volts have been made available by Tung-Sol. They were designed for use in combination with transistors. The interested research worker will be interested in further developments along these lines.

3.23. *General Considerations.* The tubes which we have found to be the most useful are given in Appendix IV. These tubes will provide an inventory for the small laboratory which will cover perhaps 90% of the elementary electronic construction which the investigator or laboratory technician will encounter. Most or all of these tubes are available in the British Empire. If they are not available, we have found that practically all tube manufacturers are extremely cooperative and will furnish a list of equivalent tube types.

We would like to repeat that a tube handbook is indispensable and that these are available from RCA, from Sylvania and from other companies at nominal prices.

Ordinarily the tubes used in a given circuit will be only a fraction of the total cost of the circuit. With this in mind we suggest that, if possible, new tubes from a reputable outlet be purchased. If, however, tubes are offered at bargain prices by reputable wholesale outlets, we consider them worth investigating.

In a few circuits to be discussed later there will be tube types not covered in the general discussion. The design and use of these tubes will be thoroughly covered in the text concerning the circuit in which they are used. In general they are highly specialized devices designed for one specific purpose.

Chapter 4

POWER SUPPLIES

4.1. ***Operating Potentials.*** As has been mentioned, vacuum tubes and transistors require voltages of various values for circuit operation. With the exception of tube heaters, which may be AC, these potentials must be direct current with a low AC component value. The most convenient source of EMF for tube circuitry is a transformer-rectifier power supply. The vacuum tube as a rectifier is discussed in 3.5, but other devices such as selenium, germanium or silicon diodes may also be used as rectifiers. The nomenclature of the various potentials has been carried down from the days when the major source of power was a battery. The "A" potential is the filament supply, the "B" potential is the plate supply and the "C" battery is the bias supply. The DC plate potentials used for tube circuit operation are called B+ and B–.

4.2. ***Vacuum Tube Rectifiers.*** The diode tube (3.5) can be used as a rectifier. If it has one plate and one cathode it is called a half-wave rectifier. A half-wave rectifier circuit together with cathode waveshape is shown in Figure 4.1. The output is pulsating DC having an

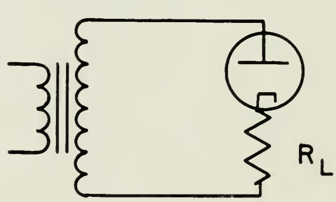


FIG. 4.1

average value equal to one half the average value of the secondary voltage. The efficiency of a half-wave is low and the output tends to drop sharply under load. The voltage regulation is therefore said to be poor. It is suitable for uses where the relatively high ripple factor can be tolerated or where the current demand does not change drastically.

The full-wave rectifier shown in Figure 4.2 conducts on both halves of the AC cycle in such a way that current flow through the cathode has a ripple frequency of 120

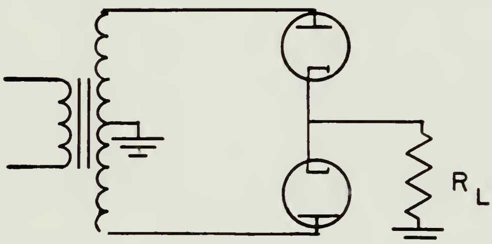


FIG. 4.2

cycles per second. Note that with the center tapped transformer the two ends are 180 degrees out of phase. Therefore, the diodes conduct alternately.

The average output voltage is higher than the output of a halfwave rectifier and the voltage regulation is much better. The ripple frequency is also an octave higher and hence makes possible the use of less filtering.

4.3. ***Filter Circuits.*** The output from a rectifier is not suitable for use as a supply voltage because of the high ripple or AC component. This must be removed or filtered.

Typical filter circuits consist of inductance in series with the load and capacity in parallel with the load. The condenser opposes any voltage change by storing energy when the voltage is high and releasing it when the voltage falls. The inductor opposes any sudden rise or fall in voltage by generating back EMF. In combination with each other they tend to hold the voltage across the output to an average value.

Filter sections may have either a choke or condenser as the input element. The choke input type gives better

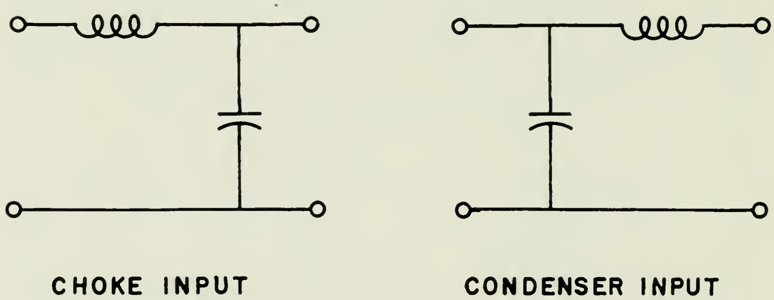


FIG. 4.3

voltage regulation but with a lower average voltage output. The condenser input is a simpler circuit but the voltage tends to rise quite high when the circuit is unloaded.

In some circuits the choke may be replaced by a resistor. If the current drain is reasonably low filtering may be quite adequate. This type of filter is often used as a de-coupling filter to isolate amplifier stages.

4.4. ***Regulator Tubes.*** Where stable operating voltages are required it is good practice to consider some automatic means of voltage regulation. The gas diodes called VR tubes are adequate if the current demand is between 5-30 milliamperes. A typical VR circuit is shown in Figure 4.4. As the load decreases the voltage across the VR tube increases. More current flows through the tube and the voltage is maintained at 150 volts plus or minus a few volts. Two tubes can be connected in series to handle higher voltages but they cannot be connected in parallel. In this case the first tube to fire will lower the voltage below the striking potential of the second tube.

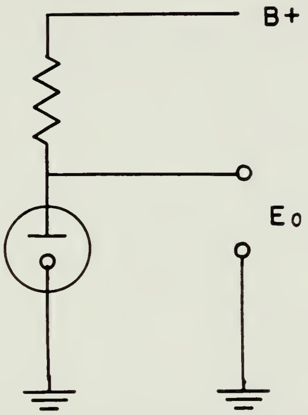


FIG. 4.4

4.5. ***Electronic Voltage Regulation.*** The regulator circuit shown in Figure 4.5 is capable of being set to extremely close voltage values, although the regulation cannot be any better than the regulation of the reference voltage. This circuit uses the plate resistance of V_1 as a variable resistor in series with the load. It automatically adjusts to the correct value required to maintain a constant voltage at the output. V_3 is a VR tube which maintains a constant reference potential for the cathode of V_2, the amplifier tube. The grid of V_2 is adjusted to a bias value that will place V_2 on a linear portion of its operating curve. When the output voltage varies up or down the operating point of the tube changes and the bias on V_1 is altered, letting more or less current pass as is required.

This is the simplest electronic voltage regulator. More complex circuits use twin triode amplifiers or pentode amplifiers for V_2 and special tubes such as the 6AS7G or 6080 for the regulator or pass tubes. The principle does not change.

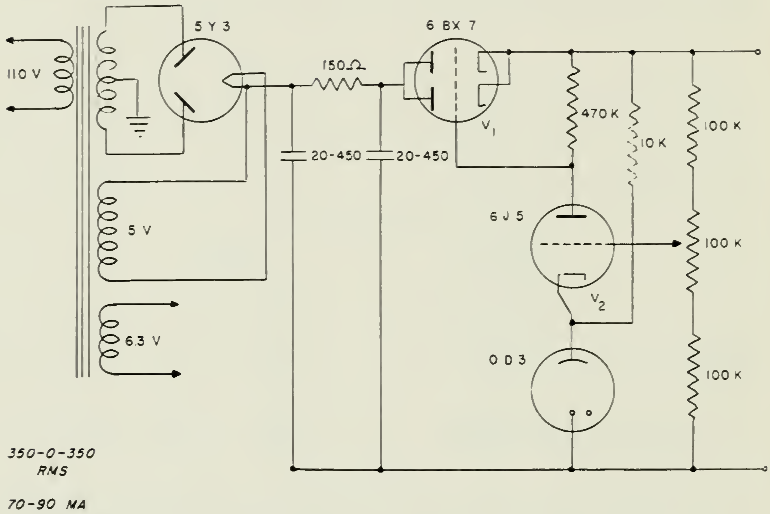


Fig. 4.5

The major objection to this circuitry is the need for using 400 or 450 VAC transformers to supply a sufficiently high potential to compensate for the drop in the pass tube. The circuitry can be modified as shown in Figure 4.6 so that the cathode of V_2 is returned to ground and the grid resistor to a negative voltage. Ordinary 350-0-350 volt power transformers can then be used. In addition, a regulated bias supply is available if it is needed.

Regulated power supplies are essential to development work and can often be built into instruments. They can be used quite efficiently to replace the two chokes and three condensers required of a choke input filter section. The savings in terms of weight and space may be worthwhile.

Regulated power supplies are commercially available to supply voltages from 6 volts to 50,000 volts. There is a wide choice of plate voltage power supplies which cover the range of 150-450 volts. We have found that the Heathkit Model PS-3 is adequate for most bench work. It ranges from 0-450 volts at 100 milliamperes with reasonably good regulation at the low price of $35.

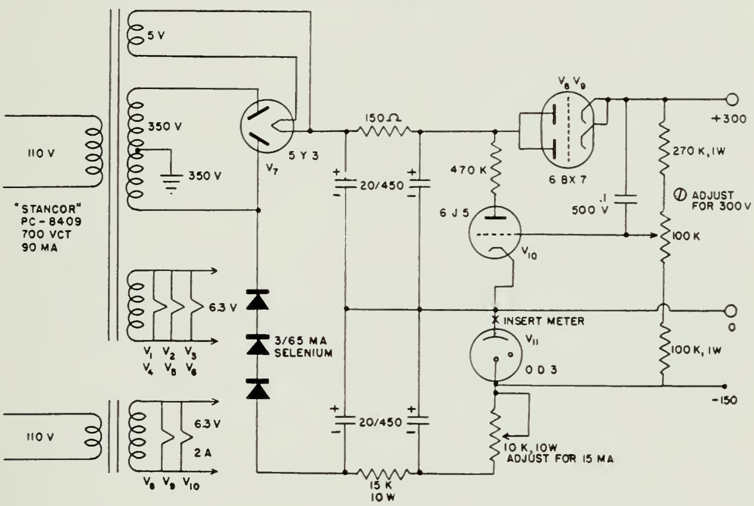


Fig. 4.6

4.6. ***Metallic Rectifiers.*** Many metals and metallic oxides are semi-conductors. They are therefore rectifiers, since they conduct quite easily in one direction but oppose the current flow in the oposite direction. Selenium rectifiers are widely used for half-wave rectifiers in radio service and as voltage doublers in TV service. There is a low voltage drop, but the back voltage that a layer of selenium can withstand is limited, so that for high voltages selenium rectifiers must be connected in series.

Within the past few years both germanium and silicon rectifiers have been placed on the market. At this time they are quite expensive but are small and do not deteriorate under use if not overloaded. We expect that in a very short time silicon rectifiers will be available at prices which compare with tube prices. Such rectifiers can be wired into circuits, occupy a very small fraction of the space taken up by a vacuum tube, require no heater current and are almost indestructible.

4.7. ***Power Transformers.*** Another basic element in the AC power supply is the power transformer. A transformer is a device which will change an AC voltage to another AC voltage. Thus, any reasonable AC voltage can be derived from the 110-120 VAC supply. The power transformer ordinarily supplies a high voltage for the tube potentials and one or more lower voltages for heater voltages. A typical transformer may supply 350-0-350 volts in a center-tapped arrangement, 5 volts and 6.3 volts or other heater voltages without center taps and be rated at 100 milliamperes for the high voltage output.

It has been our experience that the most common mistake is to over-power instruments. It has been our experience also that transformers are conservatively rated by the maker and will supply rated current without heating problems if they are adequately ventilated.

A second mistake is to choose a transformer with too high AC output voltages. It is seldom necessary to use 300 volt plate potentials. A voltage of 250 is more reasonable for most small receiving tubes and 200 volts gives an added margin of safety. We have found that a transformer such as the Stancor PC8406 with a 650 volt center tapped secondary and a 5 volt and 6.3 volt secondary is adequate for the larger part of the circuits constructed for experimental purposes. Such transformers are known as "replacement grade" items. A better grade transformer which may be "potted" or sealed in a steel case with sealing compound is available at about twice the price of replacement transformers. These are suitable for items of permanent equipment which will undergo constant or heavy usage.

The best transformers are those made to military specifications such as Mil-T-27. These transformers are made in a standard range of sizes by many different makers. They are often available from surplus outlets and are definitely worth investigating. A small amount of time spent with a Chicago Transformer catalogue or with the Radio Master will serve to acquaint the investigator with the specifications, case dimensions, etc. Often the words "hermetically sealed" in an advertisement is a clue to Mil-T-27 transformers.

It is our practice to utilize upright mounting transformers in shop construction. All Mil-T-27 transformers, most commercial grade transformers and a wide variety of replacement transformers are available in upright mounting cases.

4.8. ***Filter Condensers.*** Another important item is the filter condenser. Where space and cost is no consideration we recommend oil-filled paper dielectric condensers. For less elaborate circuitry electrolytic condensers are widely used. They are small and comparatively inexpensive. At the same time there are a few precautions which must be observed with these units. One plate of the condenser is aluminum foil. The dielectric is a thin film of aluminum oxide. The electrolytic solution is the other plate. Since the film is quite thin the capacity is high, as one of the factors governing capacity is the physical separation of the plates. At the same time the foil must be the positive pole of the condenser. Hence they cannot be connected in reverse or to AC sources without damage.

The aluminum can is usually the negative terminal. It must be insulated or isolated from other circuit elements. This is accomplished by a fiberboard outer case or by plastic mounting rings if the case must be isolated from the chassis.

Electrolytics also have a definite shelf life, at the end of which the film has been lost. Old electrolytic condensers should never be placed in circuits where they are exposed to high voltages without "forming," an operation which consists of applying voltages to the condensers. Ordinarily it is best to begin at zero and work up to the rated voltage, meanwhile observing for excessive current flow. The resistance of a formed electrolytic should be around 100K ohms. If it is considerably lower the film has been lost, if higher, it is most likely open.

Another major point is that a high capacity electrolytic appears as a virtual short circuit if thrown across a circuit when it is uncharged. For that reason if electrolytics are to be used with selenium rectifiers it is advisable to install a 50 or 75 ohm resistor between the rectifier and the capacitor. Otherwise, the initial surge of current may seriously damage the rectifier.

4.9. *Dry Cells.* When two dissimilar metals or a metal and carbon are immersed in a solution that has a greater chemical action on one than the other, a difference in potential will exist between them. This arrangement is called a primary cell. If the solution is absorbed by a filler in a sealed case the cell is called a dry cell. The common dry cell consists of a carbon center pole, a space filled with electrolyte and filler and a soft zinc case. The voltage of such a cell is 1.5 volts.

Large numbers of dry cells can be arranged in series to supply higher voltages. In the early days of electronics such batteries were the major source of EMF for vacuum tube operation. With the advent of AC rectifier circuitry the dry cell became relatively unimportant until the transistor was developed. Since transistors often work very well with 1.5 volt potentials, dry cells are again becoming an important type of power supply.

The dry cell has many advantages for such circuitry. It is relatively cheap, quite small and has a very low internal impedance so that voltage regulation is quite good. On the other hand, the dry cell has a limited shelf life and a somewhat limited active life. Voltage steadily falls as the battery is used up. Some of these objections can be overcome by the use of mercury cells.

The mercury cell produces electrical energy by a reaction between zinc and mercuric oxide in a potassium hydroxide solution. Since these cells have almost no local action until current is drawn, the shelf life is almost unlimited. They are more stable than carbon-zinc cells and are smaller in physical size for equivalent current capacity. In addition, the output voltage of the mercury cell is nearly constant until the end of its life, when the output voltage drops sharply.

At this time mercury cells are more costly than ordinary dry cells but are widely used in transistor circuitry.

4.10. ***Vibrator Power Supplies.*** A vibrator is a device which chops DC voltages into square waves at approximately 115 cycles per second. The resulting chopped DC can be used to drive the primary of a step-up transformer. This arrangement is commonly used with wet cells to supply plate potentials for mobile radio receivers and public address systems. We have found that a 2 volt vibrator and transformer can be used to make an efficient shock generator. A circuit is given in Figure 4.7 which uses a 2 volt vibrator. One word of caution. Do not operate this circuit without a load resistor. The square waves produce a tremendous current flux in the transformer windings.

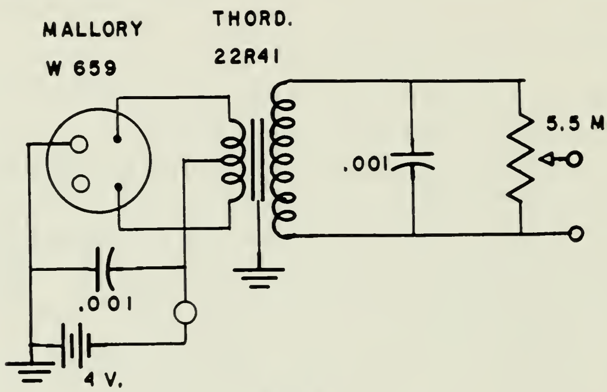


Fig. 4.7

Since the output voltage is in proportion to the current flux, several kilovolts may be produced across an open secondary. This will break down the transformer windings or deliver a serious shock to the subject.

4.11. ***Other Power Supplies.*** Not all devices for the production of power or voltage have been discussed here. There are voltage doubler circuits, for example, which work from the 110 volt line to produce a 250 volt output. For safety and good filtering we cannot recommend this or any other AC-DC circuit which is not isolated from the power line by a transformer. If there is a need for a 100 volt or 125 volt power supply a suitable transformer can be purchased for less than $3. If subjects are to be connected in any way to laboratory apparatus it is imperative that the circuit ground be returned to earth ground. A Variac, for example should never be used to stimulate subjects because it is an autotransformer with one side of the output returned to the power line. If the outlet plug is not polarized a subject can be connected directly across the power line to earth ground with possibly fatal results.

4.12. ***Other Safety Precautions.*** Well-regulated AC power supplies are lethal devices and can cause heart stoppage, broken bones, burns and other injuries. They should be treated with utmost respect. There are a few rules which should be rigidly observed in connection with power supplies.

1. Always return the ground or zero potential point to the chassis so that the chassis can be returned to earth ground if the apparatus is to be used with subjects.

2. Install power switches so that OFF is DOWN. This decreases the chances of accidentally turning equipment on.

3. Always put a bleeder resistor in power supplies to discharge high voltage condensers.

4. Use a probe or screwdriver to short filter condensers to ground before working on equipment.

5. With voltages over 300, an interlock switch should be provided to turn the power off when cases are opened.

6. Install line cord connectors so that the open or hot end is shielded or a female connection. Never make up a "suicide cord" which is a line cord with a male plug and clip connectors on opposite ends.

7. Don't become careless or indulge in senseless horseplay with electrical apparatus.

All of the safety precautions mentioned above are important but the most important of all is a healthy respect for electricity and the application of common sense.

Chapter 5

AMPLIFIERS

5.1. ***Principles.*** Although amplification has been treated earlier as a phenomenon associated with electronic tubes, further treatment of the process will be given in this chapter because of the great importance of amplifier circuits in behavioral research instrumentation.

The process of amplification consists of enlarging or magnifying signals received from an input transducer to the point where they are capable of operating an output transducer requiring increased power, current or voltage.

All amplifiers may be trichotomized as current amplifiers, power amplifiers, or voltage amplifiers. Within these classifications they may be further described as; AC amplifiers (with limited frequency range), broadband AC amplifiers (commonly known as video amplifiers) and DC amplifiers which faithfully reproduce frequencies from several hundred per second down to zero cycles or straight DC. Each amplifier has a specific application and for most purposes, these types are not interchangeable.

5.2. ***Filters.*** In working with bioelectric amplifiers it is usually found that such instruments will provide undistorted and faithful amplification of signals within a limited range of signal frequency. EEG amplifiers, for example, pass frequencies from 1.2 cycles per second up thru several hundred cycles per second. These characteristics are determined by the basic design of the amplifier, most importantly, by the coupling between stages. Such coupling is usually provided by means of capacitors, resistors or inductors which serve to filter out certain components of the signal. Another way of looking at the filter action is to say than an electrical *underscoring* of the desired range of signal frequencies is obtained. It is therefore important to understand how successive stages of an amplifier are coupled and how this serves to produce a filter action.

In Chapter II it was stated that capacitors and inductors behaved quite differently with respect to the impedance they presented to alternating currents of different frequencies. Capacitors offer very high impedance at zero cycles (DC), but their impedance decreases as the signal frequency increases.

Inductors offer only the ohmic resistance of their windings at zero cycles but their impedance increases as the signal frequency increases.

There are three general types of filter circuits. The highpass filter will pass all frequencies above a given

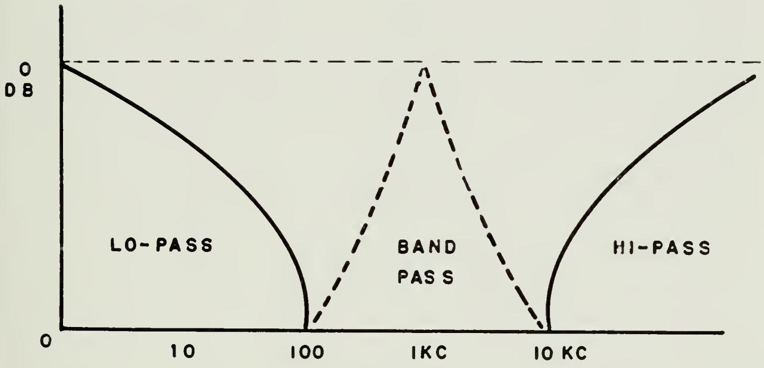


Fig. 5.1

frequency F_0. A lowpass filter will pass all frequencies below a given frequency, while a bandpass filter will pass a relatively narrow band of frequencies and attenuate all frequencies above and below this band. Characteristic curves of these filter are given in Figure 5.1.

It may be noted in these curves that the "cutoff" of each filter, that point at which the signal begins to be attenuated, is not really a point but occurs as a gradual slope. The slope of this cutoff may be varied somewhat by certain factors of the design of the filter.

5.3. ***Low Pass Filters.*** A typical lowpass filter is shown in Figure 5.2. Note that the filter is double ended, that

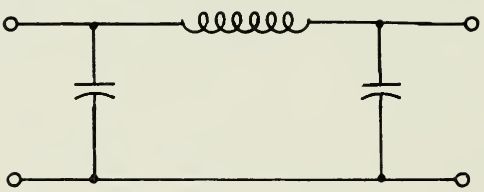


FIG. 5.2

there is no specific input or output terminals and that it is symmetrical.

The operation of the filter is as follows: At low frequencies and DC the impedance of the inductors is practically zero while the impedance of the capacitor is quite high. There is little signal attentuation at low frequencies therefore. As the signal frequency begins to rise, the inductors begin to pass less and less AC while the condenser shunts more and more of the signal to ground. At a point determined by value of inductance and capacitance in the circuit, the response begins to cut off. The rate of cutoff may be increased (the slope of the curve made sharper) by connecting two or more sections in series.

5.4. ***High Pass Filters.*** Figure 5.3 shows a typical highpass filter circuit. Note that it resembles a lowpass filter circuit except that the positions of the capacitor and inductor have been interchanged.

At high frequencies the impedance of the capacitor is small while the impedance of the inductor is quite high. The signal is therefore passed with little attenuation. As the signal frequency decreases, the capacitor begins to offer increasing impedance and the inductor provides an increasingly better path to ground.

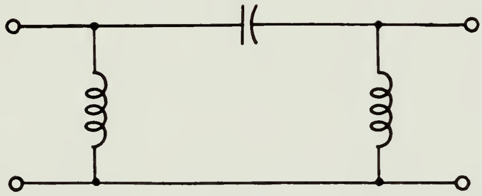


Fig. 5.3

Again, the sharpness of cutoff is determined by the values of L and C and may be increased by adding identical sections.

5.5. ***Bandpass Filters.*** While this type of circuit is infrequently encountered in bioelectric amplifiers, it is discussed here as an illustration of the differential effects of series versus parallel LC circuits.

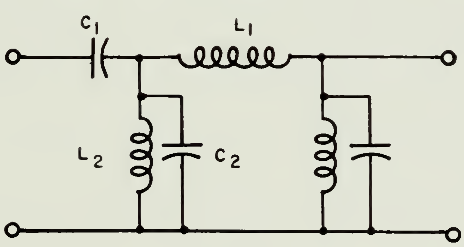


Fig. 5.4

The action of this filter is best described in terms of the total impedance offered by series and parallel elements.

Considering C_1 alone, it can be seen that its impedance is highest at zero signal frequency and lowest at infinitely high frequencies. The impedance of L_1 alone, is opposite to that of the condenser, i.e., lowest at zero signal frequency and highest at high frequency.

Now at some point, F_o, of signal frequency, these elements offer equal reactance. At this point, attenuation of signal will be minimal.

The parallel elements L_2 and C_2 offer the same characteristics with respect to signal frequency. The inductor, L_2, offers low impedance at low frequency and C_2 offers low impedance at high frequencies. At the frequency at which their reactances are equal, attenuation will be less than at any other frequency. Thus the shunt impedance will be lowest at the signal frequency F_o. If the optimal frequency F_o of the parallel section is the same as that of the series section, F_o will be attenuated less than any other frequency.

At the same time, if the ratio of reactance to resistance in L_2 and C_2 is relatively high (high Q) the circuit will resonate at F_o so the network is not entirely passive. There will be some voltage gain which in turn will afford a slight boost to signal frequencies at F_o.

5.6. ***Applications.*** The most frequent use of LC filters is found in the design of AC power supplies. The resistor, capacitor, inductor network following the rectifier is a lowpass pi-section filter which provides relatively pure DC by attenuating all higher frequencies.

Filters are also found in EEG amplifiers with function switches for EMG and ECG. The switch in bandpass filters is designed to pass signal frequencies appropriate to the phenomenon under study and to eliminate all other frequencies.

Filters are also used in circuits where random or experimental "noise" must be removed from the signal. For example, it is possible to record various bioelectric phenomena while deliberately passing an AC signal into the preparation as a stimulus. The stimulus frequency must fall outside the signal band and an appropriate filter section inserted between the preparation and ensuing instruments.

In audio work, filters may be used to emphasize or de-emphasize selected bands or portions of the audible spectrum. They may be used to modify the response curves of amplifiers in accordance with experimental requirements.

5.7. ***RC Coupling Networks.*** Most AC amplifiers are RC coupled. This means that one stage of the amplifier is connected to the succeeding one by means of resistors and capacitors. Transformers may be used for coupling but are rarely used in bioelectric work.

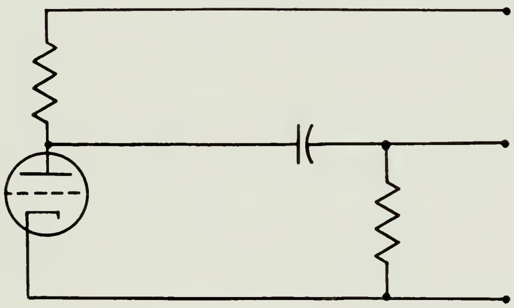


FIG. 5.5

In RC coupling, the load of a preceding stage is a resistor and the signal to lead into the grid of the tube in succeeding stage by means of a condenser, usually called "blocking" or "coupling" condenser. The signal is taken between this condenser and a grid impedance, usually a resistor. This is shown in Figure 5.5.

It may be seen that the impedance of the grid resistor is constant with respect to frequency but the impedance of the condenser is not. This combination, therefore, forms a simple highpass filter. The lower limits of response of an AC amplifier with RC coupling is determined by the values of the grid resistor and coupling condenser. The output of the amplifier will be flat with decreasing frequency to a point and then will begin to fall six decibels per octave of signal frequency. The frequency at which the voltage divides in a ratio of .707 across each element is called the "half power point."

Some explanation may be needed here. Due to phase shift, the voltage developed across both R and C will be 70.7% of the input when the reactances are equal, not 50%. This point is called the half-power point because it represents a 3 db drop in power.

The high frequency response of an amplifier is determined by two factors; the shunt capacity of wire and tube elements to ground, and, the input capacity of the tube elements.

Ordinarily, this is negligible when pentode tubes are used but is a definite factor in triode AC amplifiers due to the Miller effect. The Miller effect causes the real input capacity of a triode to be amplified by the gain of the stage, consequently the higher the "mu" of the triode, the greater the input capacitance.

5.8. ***Push-Pull Amplifiers.*** Many of the basic concepts of the amplifier are discussed in Chapter III. While those principles apply to all amplifiers, not all amplifiers follow the same design. The push-pull amplifier, for example, is often used in behavioral instrumentation because it provides stability and freedom from artifact not found in the single tube amplifier. The general configuration of the push-pull amplifier appears in Figure 5.6.

Inspection shows that the circuit is essentially two single amplifiers connected "back-to-back" with common grounds. When an out of phase signal is applied to the grids, one grid goes positive, the other goes negative and

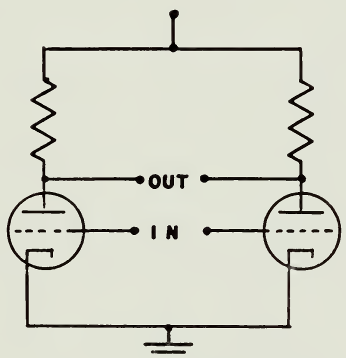


FIG. 5.6

the two plates swing in opposite directions. The amplified signal appears as the potential difference between the plates of the two tubes. It is this feature which gives the push-pull amplifier its particular advantages.

Since the output appears as the difference between the two plate potentials, any change in grid voltage or plate voltage (from power supply instability, etc.) will change each tube potential by an equal amount and there will be no difference in the signal.

Since the current drawn by a pair of tubes is nearly constant, they can be biased by a common cathode resistor without degenerative feedback. Thus, the bias does not vary according to the signal input. If the cathode resistor is made nearly equal in size to the plate resistors but returned to a negative voltage, it is possible to discriminate against inphase (noise) signals by a factor of nearly 1:100. Two such stages will provide a noise discrimination of nearly 1:10,000.

For optimal results, tubes for the initial stages of a push-pull amplifier should be selected for low noise and be closely matched with respect to their dynamic characteristics. If this is not possible, a potentiometer should be used as part of the plate load so that each plate load may be adjusted to give equal amplification. Many EEG amplifiers use dual triodes because of their lower noise figures and the fact that both sections are in a single envelope.

5.9. *Phase Inverters.* Proper operation of the push-pull amplifier requires that the input signals be 180 electrical degrees out of phase. Since the signal will usually be single phase it is necessary to split it and invert the phase of one portion. Such a circuit is called a "phase inverter."

The simplest phase inverter is a transformer with a single primary and a center-tapped secondary. The outside ends of the secondary winding will be exactly 180 degrees out of phase. Although transformer coupling is ideal for use in speech frequency amplifiers, the relatively narrow range of frequencies passed by any transformer severely restricts its use.

The authors have found that the cathodyne or split load phase inverter works well for most audio use. This consists of an input stage directly connected to a second stage with equal plate and cathode resistors. The final output is a signal with equal amplitude but with the necessary phase inversion. A circuit suitable for audio use in shown in Figure 5.7.

In this circuit, the voltage amplifier is a pentode section of a dual unit tube, the 6AN8. The triode grid is tied to the pentode plate. The plate and cathode resistor values are such that the tube sets its own bias in much the same manner as a cathode follower. The input capacitance is low. The gain of the pentode stage is about 100, while the gain of the triode stage is unity.

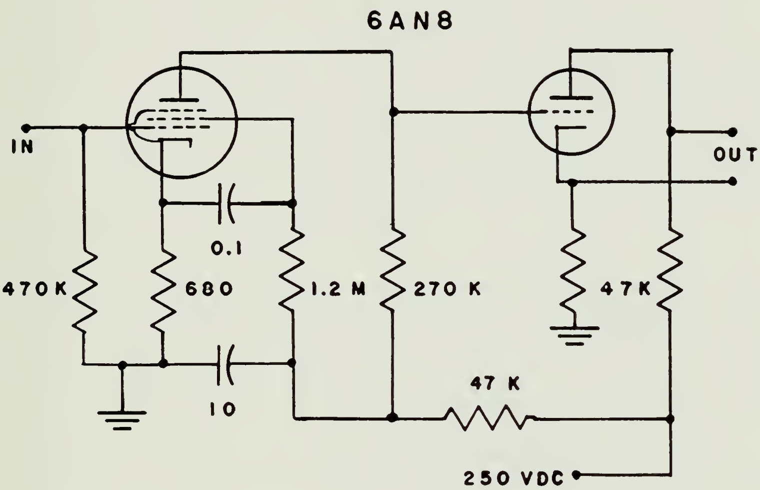


FIG. 5.7

5.10. *Direct Coupled Amplifiers.* Most bioelectric phenomena encountered in behavioral research are characterized by relatively low frequencies (100 cps down to DC) and low potentials. Ideally, therefore, the perfect amplifier should have a gain of 10^6 and a flat response from 0 to 10,000 cycles per second. Unfortunately, such an amplifier cannot be built.

The laboratory amplifier is therefore a compromise. AC amplifiers are used for frequencies from 4 cycles to 5 megacycles while direct coupled DC amplifiers are used for signals from 0 to about 200 cycles per second.

Direct coupled amplifier have no transformer or RC coupling networks for the obvious reason that such an arrangement would completely block a DC signal. The grids of each stage are therefore directly tied to the plate of the preceding stage. This would mean that the grids of succeeding stages must be higher in potential than that of the stage feeding them.

DC amplifiers also suffer greatly from drift, a change in output in the absence of an input signal. This may occur for many reasons but among the hardest to control are those of fluctuations in heater temperature. Any change in the operating parameters of a tube will influence manyfold the signal of succeeding tubes.

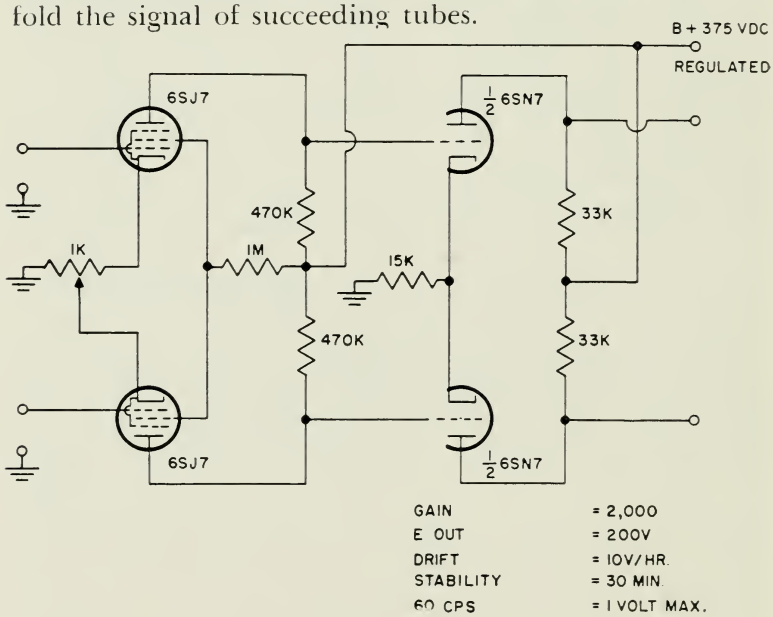


Fig. 5.8

In *5.8* the push-pull amplifier with a large cathode resistor was mentioned. This amplifier is sometimes called a "longtailed pair" and at times a differential amplifier.

Since like the cathodyne this circuit will set its own bias if the grids are elevated above ground, a DC cascade arrangement can be used. The circuit shown in Figure 5.8 is a medium gain 2 stage amplifier which might be used for PGR or oscilliscope amplifiers. The 6SJ7 input stage has a gain of approximately 200 when fed push-pull, although it may be fed single ended by grounding one grid. The triode output stage will have a gain of approximately 10. Thus, the overall gain is about 2000-3000. The circuit will be stabilized in approximately 30 minutes. The hum level is on the order of 0.1% at maximum output level. It would be possible to add another stage if the output stage has a plate supply of 600 volts, but drift problems become rather severe.

With any DC amplifier used in bioelectrical work, the input stages should be fed from an extremely stable AC power supply (by using a constant voltage transformer) or from batteries to avoid drift and random fluctuations in the output signal. With an extremely high gain amplifier, fluctuations in cathode emission will also cause drift, so that batteries may be profitably employed for heating filaments. If a battery supply is used for both filaments and plate, and if the circuit is carefully constructed and all spurious noise eliminated, the lower signal limit will approach the thermal noise level of the circuit wiring and resistance.

Low-level DC amplifiers are not circuits for laboratory construction unless the laboratory is unusually well equipped and staffed. Several commercial DC amplifiers are available for low-level use at reasonable prices. The General Radio electrometer and the Sanborn amplifier are very adequate instruments.

High level amplifiers are feasible for laboratory construction and are useful for PGR work, etc.

5.11. ***Power Amplifiers.*** The power amplifier serves to convert the relatively low-powered signal voltages to the point where they may drive the output transducer.

The signal is first amplified with respect to its potential. This initial section of the amplifier is termed the voltage amplifier. The signal is then fed into the power amplification stage, usually a single stage with a transformer for a load.

The tubes of this stage are specifically designed to handle fairly high currents and voltages. The high voltage signal is fed into the primary of the transformer. This is a step-down transformer which converts the low amperage, high voltage signal into a low voltage, high amperage output. The secondary of this transformer may develop as much as 8 volts across 8 ohms of load impedance or a power of 8 watts.

This 8 watts of power can do work. It can cause displacements of a speaker cone and produce sound or deflections in a magnetic pen motor. It is the final representation of the signal voltage, faithfully reproduced as to waveform, frequency, etc., but enormously increased in power.

The general function of the power amplifier is that of converting voltage to power and of driving some impedance matching device such as a transformer so that a major portion of the output of the amplifier may be transformed into useful work.

5.12. ***General Purpose Amplifiers.*** While many excellent amplifiers are available commercially for bioelectric purposes, excellent instruments are available quite reasonably in the form of "hi-fi" amplifiers. These may be purchased in kit form from Heathkit or Allied Radio. They may be constructed by the relatively unskilled and can be modified to put out 75-100 volts across the 500 ohm tap usually found on the output transformer. They are then quite useful for driving stimulus generators for faradic shock, tactile stimulation, etc., as well as for audio work.

These amplifiers achieve wideband frequency response by the use of negative feedback. Part of the signal is taken from the output and fed into the input 180 electrical degrees out of phase with the signal. Thus any distortion arising *within* the amplifier is cancelled out because there is no opposing signal at the input. At the same time caution must be exercised to avoid excessive use of feedback, particularly if additional phase shift exists in the circuit since this would cause inphase feedback, reinforcement of the signal, and destructive oscillation.

The feedback resistor of any amplifier should be optimized by the use of an oscilloscope monitor on the output. It is only by this means that ultrasonic oscillation may be detected and consequent distortion avoided.

5.13. ***Cathode Followers.*** Although the cathode follower is generally included in a discussion of amplifiers, it has a gain of less than unity and is primarily used for impedance matching purposes. In suitable configurations, the cathode follower may display an input impedance of nearly 40 megohms, an input capacitance 1/40 of that of the conventional amplifier input and an output impedance of several hundred ohms.

In the diagram, Figure 5.9, the cathode follower is compared with a plate circuit triode amplifier.

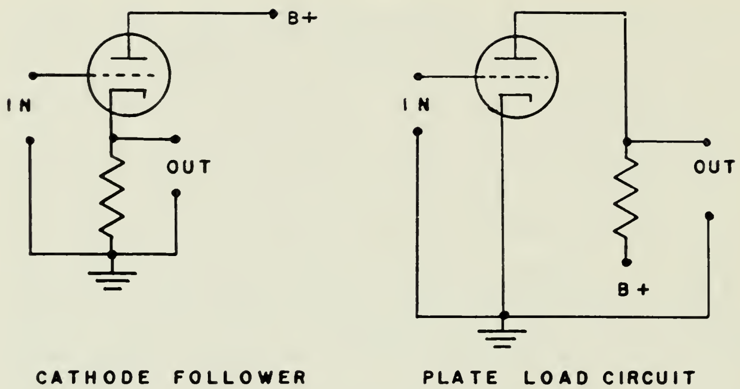


FIG. 5.9

The load resistor in the cathode follower circuit is in the cathode circuit rather than the plate circuit as in the conventional amplifier. The entire signal developed across the load is fed back from cathode to grid so that complete degeneration or 100% negative feedback occurs. Although no voltage gain is possible, the cathode follower can furnish power gain due to the differences between its input and output impedances.

The gain may be calculated by:

$$\text{Gain} = \frac{\mu R_k}{R_p + R_k\ (\mu + 1)} \qquad \textit{Formula 5.1}$$

Since mu occurs in the numerator and mu plus 1 in the denominator, the fraction is always less than unity.

The output impedance of the cathode follower is that of both the cathode resistor and the effective AC plate resistance. It is resistive and is expressed by:

$$Z_o = \frac{R_p\ R_k}{R_p + R_k\ (\mu + 1)} \qquad \textit{Formula 5.2}$$

The size of the cathode resistor is an important consideration in the design of the cathode follower and is given by the following formula:

$$R_k = \frac{Z_o R_p}{R_p - Z_o (\mu + 1)}$$ *Formula 5.3*

where Z_o is the output impedance, R_p the plate resistance of the tube and mu, its amplification factor.

Since the input impedance is so very high, the cathode follower is useful in bioelectric work. Where an animal preparation must be maintained at a considerable distance from amplifiers and recording instruments, the cathode follower may be located close to the preparation where it presents neglible loading effects on the source and the low output impedance permits the use of extremely long leads to the amplifier without the introduction of noise and hum.

It is also useful for driving audio lines since an output impedance of 500 ohms may be achieved without the use of a transformer.

Chapter 6

OSCILLATORS

6.1. ***Feedback Loops.*** An oscillator has an input between the control element and ground. The output is taken between a suitable impedance and the tube or transistor. The output will differ from the input by a phase angle of 180 degrees. The purpose of a positive feedback loop is to add an additional 180 degrees phase shift so that the output will arrive at the input exactly in phase. Under these conditions the output will reinforce the input. If the stage has a gain of 1 or more the circuit will oscillate at a periodic frequency.

Oscillations are self-starting because any random shift in plate current is amplified and returned to the control element as an input signal. If the gain is substantially greater than 1 the entire system will reach an equilibrium very shortly after oscillations begin. If the gain is very high the oscillations will reach levels defined by the circuit parameters and is said to be "bottomed." Under these conditions the output will be characterized by sharp rise times and will differ greatly from sinusoidal output.

If the gain is limited the output can be made to be a sine wave. It should be noted that the output of an oscillator is not limited to a sine wave output. Any device which will deliver repetitive waveforms without an input is an oscillator and also a time base generator.

6.2. ***Transformer Oscillators.*** Perhaps the simplest oscillator is a vacuum tube with a transformer as the plate load. Two possible sets of output connections are available at the secondary. One method of connecting the windings back to the grid will give negative feedback which is out of phase with the grid. The other connection will give the phase shift necessary to cause oscillation. If the gain of the stage is greater than unity the circuit will oscillate at a frequency determined by the inductance of the coil and the distributed capacity of the windings, or, the capacity of a tuning condenser connected across the secondary or primary. All such LC circuits suffer from the fact that they cannot be tuned over a wide range because the frequency varies as the square root of the capacitance and inductance of the tuned circuit. A tuning capacitor can be varied over a 10/1 range, but the effective change in resonance will be over a 3/1 range. LC oscillators are widely used as radio-frequency oscillators because the coils can be made physically small and the tuning range is adequate. LC audio oscillators are apt to be bulky, since the required inductors must be in most cases built with iron cores. The LC audio oscillator is quite useful in the research laboratory if a single frequency is desired.

The LC oscillator has an added advantage in that the frequency is largely dependent upon the circuit L and C so that tube variations and plate current changes have little effect.

6.3. *RC Phase Shift Networks.* A network such as that shown in Figure 6.1 will shift all frequencies by some phase angle but will shift one frequency by 60 degrees. Three such networks in series will shift the input by 180 degrees. Such an oscillator is called a phase shift oscillator. This oscillator is ideal for single frequency applications because it requires few components and is quite stable. The frequency cannot be readily changed without changing the entire network.

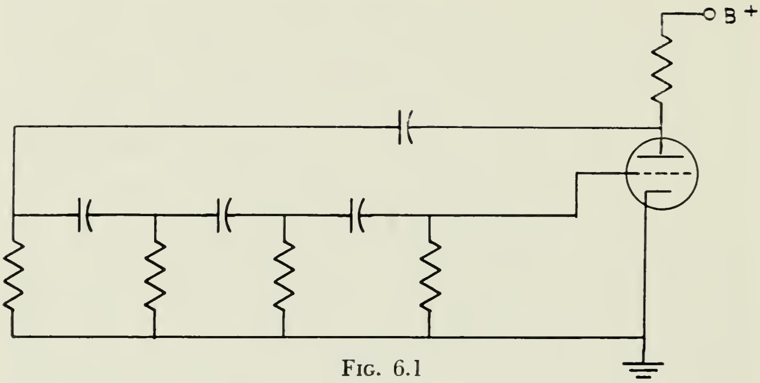


Fig. 6.1

6.4. ***Wein Bridge Oscillators.*** The circuit shown in Figure 6.2 is called a Wein bridge oscillator. The bridge between the output of V_2 and the input of V_1 will pass only the frequency which can be changed by varying either R or C. In the circuit shown the resistors R_1 and R_2 are changed simultaneously. At any time the amplifiers V_1 and V_2 will amplify noise which is actually composed of a wide range of audio frequencies. The positive feedback loop through the selective bridge allows only F to be amplified while the negative feedback loop degenerates all frequencies including F. The ratio of selectivity in the bridge versus degeneration across the cathode resistor R_k must be greater than unity if the circuit is to oscillate.

At the same time it must be kept near unity if the output waveform is to be a pure sine wave. The lamp used as R_k is nonlinear because the tungsten filament resistance increases with the passage of current. Consequently, if V_1 or V_2 start to increase in gain the extra current through R_k will cause the negative feedback to rise. The gain will then fall or remain steady.

This operation may take from 1 to 10 cycles. The output will then bounce or jitter. The change may be as great as 2 decibels. In audio or faradic stimulation this represents more than one J.N.D. of intensity. For that reason the operator should carefully note any such tendencies in RC oscillator applications.

The construction of a stable RC oscillator is somewhat difficult, but we have found in several instances that it was feasible to include this circuit in research equipment. It may be calibrated against another reference oscillator. If a fixed frequency oscillator is needed, R_1 and R_2 can be replaced by one watt carbon resistors of the desired value. Several may be switched in and out of the circuit if necessary. A series switch, for example, with 10 equal resistors would provide a decade relationship between the fixed frequencies.

6.5. ***Beat Frequency Oscillators.*** The beat frequency oscillator or BFO such as the General Radio 1304 is highly desirable for research in which extreme stability and accuracy of calibration is desired.

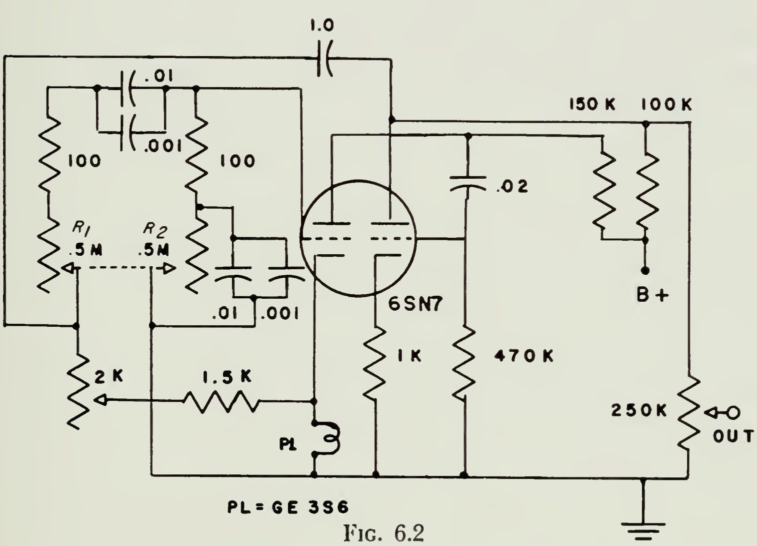


Fig. 6.2

The BFO has the peculiar advantage that it can be swept through the audio spectrum without band changing or switching. This alone makes it valuable, but since the output represents the difference component between two radio frequencies, tuning produces no serious amplitude changes. Thus, the 1304 is flat to within plus or minus 0.25 decibels from 20-20,000 cycles per second.

The 1304 is an extremely precise signal generator. A beat frequency oscillator must be quite stable. Ordinarily the construction of a BFO is beyond the capacity of the laboratory shop, but it has been our experience that for some research there is no substitute. The major consideration in the purchase of a BFO is cost. They are quite expensive but at the same time a wise investment.

6.6. ***Other Commercial Oscillators.*** For routine shop work or for the teaching laboratory RC oscillators are entirely satisfactory. We have found that the Hewlett-Packard 200 series oscillators are worthwhile instruments, but that the kits furnished by Allied Radio or Heathkit are entirely adequate and quite a bit less expensive.

Chapter 7

TIMING CIRCUITS

7.1. ***Timing Operations.*** One of the most important measures is that of time. The earlier studies in reaction time, the categorizing of EEG rhythms as having a definite frequency, the speed of neural conductivity and other fundamental experiments in the behavioral sciences hinge upon the accurate measurement of time. Man's first attempt at timing was by repetitive natural phenomena, such as sunrise and sunset or periodic phases of the moon. As science progressed, these periods were accurately divided by the use of the pendulum. With the development of radio it was discovered that the vibrations of an excited quartz crystal provide an even finer and more accurate measure of time. The vibrations of excited cesium atoms are now used as time bases. The trend is towards ever-increasing precision of time measures as man probes into the physical world about him.

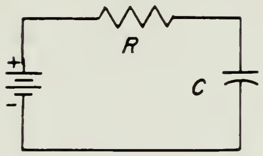
7.2. ***Timing in the Behavioral Sciences.*** At the present time work in psychology and neurology has not progressed to the stage where microsecond and fractional microsecond timing is useful. There have been some studies with extremely short visual stimuli, but for the most part the need for accurate timing past the millisecond range has not arisen. We have found that a laboratory standard which will read to 1 microsecond is adequate for most purposes.

7.3. ***Electronic Time Bases.*** Electronic measurement of time is the most accurate of all measurements. Electronic time bases for laboratory work in the behavioral sciences are usually derived from crystal oscillators, LC oscillators or RC discharge curves. The majority of the circuits to be discussed in this chapter are medium precision medium length circuits based on RC discharge curves. RC timing circuits fit well between time ranges longer than 1 second, where synchronous clocks can be used and time ranges shorter than 1 millisecond, where the most practical course is to buy precision equipment.

7.4. ***RC Charges.*** A condenser may be considered as a reservoir or container for an electrical charge. The energy which can be stored in a condenser is a function of the source impedance from which the charge is drawn, the capacity of the condenser, the EMF of the charging source and the time during which the charge is allowed to accumulate. The voltage across a condenser would reach the EMF of the source in zero time if the source could supply infinite current at zero resistance. Since this is impossible, a finite time is required to charge a condenser to some fraction of the source voltage and infinite time is required to charge a condenser to the source voltage. A most convenient fraction is the Time Constant or RC constant. The time in seconds required to charge a condenser to 63% of the applied voltage is given by the resistance in megohms times the capacitance in microfarads.

The time required to charge any capacitor through any resistance to any fraction of the applied voltage is given in Figure 7.1 below. Again, the simplest expression is given when R is in megohms and C is in microfarads. Time will be in seconds. Eb is the applied voltage, e is the base of natural logarithms and t the time.

This is an exponential relationship. Therefore, equal increments of time will not be accompanied by equal increments of voltage across a condenser.



$$V = E_B\,(1 - e^{-t/RC})$$

FIG. 7.1

7.5. ***RC Networks as Timing Devices.*** Without regard to the nature of the relationship, it can be seen that by the use of appropriate combinations of resistance and capacitance, a voltage can be made to reach a given value at a specific moment in time. Voltage sensitive circuits can be attached to such a network and can be caused to function after a specific time delay. A simple neon oscillator is perhaps the best configuration to use as a demonstration. A gas tube has a firing point. When the applied voltage

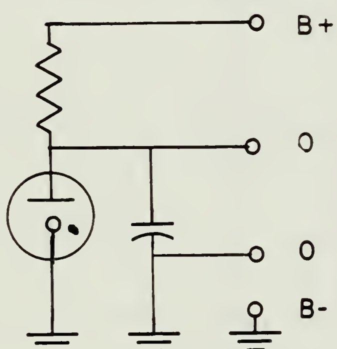


FIG. 7.2

reaches this point the tube will conduct. The tube will extinguish itself if the generator cannot supply enough current to keep it ionized. In the circuit shown in Figure 7.2 a condenser is connected in parallel with the tube.

When the voltage is applied the tube will not fire because the uncharged condenser is for a moment a short circuit. After a time it will charge so that the potential across the condenser and hence the tube will be high enough to fire the tube. The tube cannot draw enough current through R to maintain ionization, so it is extinguished. The re-charge cycle then is repeated. Such a device is sometimes called a "relaxation oscillator." A thorough understanding of the principles involved will aid in the mastery of RC circuitry.

7.6. ***Thyratron Oscillators.*** Such an oscillator may be improved and stabilized by substituting a thyratron for the neon tube. The RC network remains in the plate circuit. Tubes such as the 2D21, 2050 and 5696 are commonly used. The grid is biased with a negative voltage

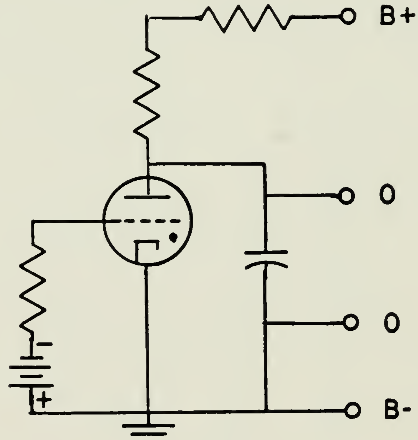


Fig. 7.3

and will keep the tube cut off until the rising plate voltage over rides the bias. A thyratron oscillator is shown in Figure 7.3. Such a circuit is sometimes called a sawtooth generator because of the waveshape of the output. This circuit has been widely used as a sawtooth sweep generator for use in oscilliscope circuits. A sharp positive spike may be taken from across the cathode resistor. Since the output impedance is relatively low, such a circuit can be used for tissue stimulation.

7.7. *Thyratron Timer Circuit.* The thyratron can be used for single-shot timing in a relatively simple circuit. When used to time 1 second periods it will stabilize in an hour to plus or minus 1 part in 10,000. In the circuit shown in Figure 7.4 it can be seen that when the grid

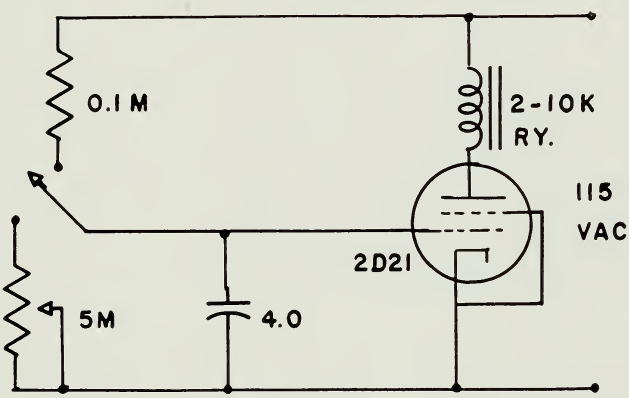


Fig. 7.4

is connected to one side of the 110 volt AC line and the cathode to the other side current will flow from cathode to the grid. The grid has become the plate of a gas diode. A negative voltage will build up across the grid leak condenser. When the switch is thrown over to its alternate position the negative charge remains and the tube will be cut off until the charge on C leaks off through R to the firing bias. This is the simplest one-shot electronic timing circuit. Since the plate current flow is quite high, relays can be operated. By using multiple contact relays elaborate logic networks can be devised and complex timing operations carried out.

7.8. ***A Bootstrap Circuit.*** Both of the previous circuits are designed without regard to the exponential nature of the RC charge-discharge curves. In addition, thyratrons are somewhat sensitive to light and are definitely affected by hard radiation. (Radioactive materials are at times deliberately placed near gas tubes. The radiation provides ionized paths and stabilizes the firing point.)

If more precision is desired or if it is necessary further stabilize a timing circuit "hard" or vacuum tubes may provide an answer. Various methods may be used to linearize an RC curve. In general these methods employ some method of constant charging current regulation. They are sometimes called "bootstrap" circuits. In the circuit shown in Figure 7.5 the grid of V_2 is tied to its cathode. As current flows through the tube and charges the condenser, the grid rises and causes more current to flow. Consequently the output across the condenser is quite linear.

The grid-condenser junction is tied to the grid of a blocked oscillator. V_1 is cut off by the positive voltage on the cathode until the grid voltage rises above the cutoff point. When the tube begins to conduct the transformer causes the grid to go heavily positive for a short time. Since the transformer is resonant at some high frequency due to internal capacitance between turns, it provides a flywheel effect which carries the grid through one cycle and causes it to go negative. This discharges the condenser and cuts the plate current of V_1 off again. The bootstrap tube begins to conduct once more because the discharged condenser acts as a momentary short circuit and the tube has no bias. The process is then repeated.

This bootstrap circuit can be operated with times as long as 10 seconds, but the high frequency range is limited because of the time required by the blocking oscillator to dump the charge. Dickensen (5) lists several alternative bootstrap timer circuits. It must be noted that since the charge curve is linearized, a longer portion of the charge curve can be used. This circuit effectively multiplies the

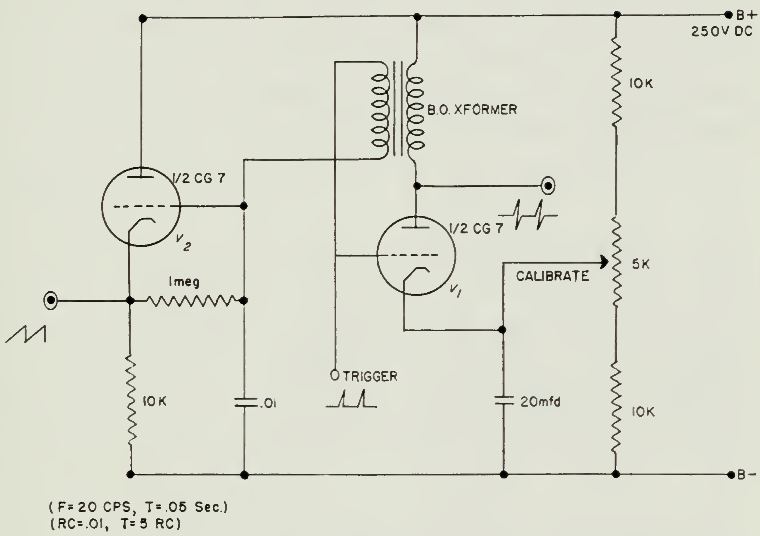


Fig. 7.5

value of the RC network by some factor which is proportional to the transconductance of the tube. For a 6SN7 this factor is approximately 5 times.

Positive and negative spikes can be taken from the plate of the oscillator tube. A sawtooth can be taken from the cathode resistor of the bootstrap tube.

7.9. ***Phantastron Circuits.*** There seems to be much confusion concerning phantastron circuits. They may be called "Miller circuits," bootstrap circuits, "capacity multipliers" and many other names. The true phantastron is a linear time base generator possessing inherently high accuracy and can be controlled by linear changes in a DC voltage.

Its operation is based upon the transitron characteristics of multielement tubes. The supressor grid of a pentode tube can control the plate current flow but not the screen grid flow. When the plate current flow is made quite small there is a point at which the cathode current is transferred to the screen grid-control grid circuit. In Figure 7.6 the screen grid is tied to the supressor grid so

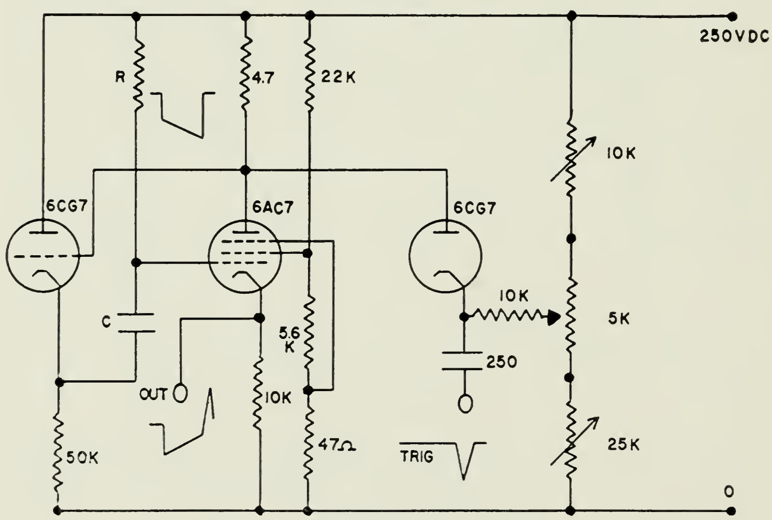


FIG. 7.6

that when the screen is not conducting the potential on the supressor grid is raised. This causes the plate to conduct quite heavily, since grid 1 is at zero potential.

If the timing cycle starts with the plate at a high potential the plate will attract most of the cathode current. Since the screen grid draws less current the potential at the screen and supressor will remain relatively high, increasing the plate current flow. At the transitron point the cathode current will suddenly transfer to the screen grid because of the lowered plate potential. This in turn cuts the plate off and the plate potential rises suddenly to its earlier condition.

If the cathode bias is made high, the tube is cut off until it is triggered. Plate rundown is initiated by the trigger voltage. In order to delay the rundown a capacitor is placed in the grid circuit. Since one end of the capacitor is tied to the plate by the cathode follower, the plate and grid run down together and the discharge curve of the condenser is kept linear.

Proper values of bias and resistance in the screen grid circuit will cause the phantastron to recycle when the plate reaches cutoff. This type of phantastron is used as a sweep generator in precision oscilliscopes. It is also the basic circuit in the Tektronix 162 Waveform Generator, a commercial physiological timing and stimulus waveform generator.

7.10. ***Multivibrators.*** The multivibrator is one of the oldest hard tube relaxation oscillators. It was widely used as a medium precision time base generator in early radar circuits and is a basic circuit in television receivers. The multivibrator is a square wave generator which can be locked in synchrony or "sync" with a higher frequency.

The multivibrator is a pair of RC coupled amplifiers connected in a ring with the output of the first amplifier feeding the input of the second. The second then feeds back into the first. The 180 degrees phase shift necessary to sustain oscillation is thus provided. Such an oscillator will then oscillate at a frequency determined by the gain of the tubes, the cutoff voltage and the time constants of the two RC networks. These parameters are related in Equation:

$$T_1 = \left(Rg_1 + \frac{RL_2 \, R_p}{RL_2 + R_p} \right) C_1 \; \text{Log E} \left(\frac{Eb - Em}{Ex} \right) \qquad \textit{Equation 7.1}$$

7.1 where T is the time of cutoff of one tube, Rg is the value of the grid resistor in megohms, Cg is the capacity of the coupling resistor in microfarads, Emax is the cutoff plate potential, Emin is the lowest point reached by the plate potential and Ex is the cutoff voltage for the tube. Essentially T is the time required for the condenser to discharge to a point where the tube can again conduct.

A typical multivibrator is shown in Figure 7.7. Any chance drop in the plate voltage at V_1 will cause a negative voltage to appear at the grid of V_2. This in turn causes

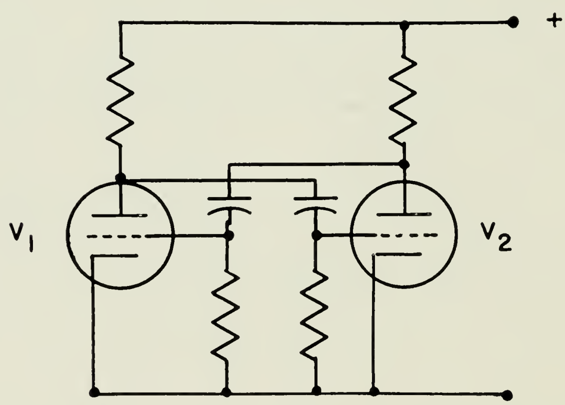


Fig. 7.7

the voltage to rise at the plate of V_2. This rise immediately appears at the grid of V_1. In a matter of microseconds the seesaw process runs away and ends with V_2 driven below cutoff and V_1 drawing maximum current. As soon as the negative charge on C_2 leaks off to Ex the tube will fire and the cycle will repeat with V_1 being cut off and V_2 conducting.

By a simple modification this circuit can be converted to a univibrator or monostable multivibrator. The two cathodes are coupled across a common resistor and the grid of V_2 is returned to the cathode while the grid of V_1 continues to go to ground. V_2 then operates at zero bias, draws more current than V_1 and can cut V_1 off until a positive pulse is applied to the grid of V_1. The negative voltage at the plate of V_1 causes regeneration. V_2 will be cut off until the negative charge leaks off C_2 through R_2.

7.11. ***Stabilizing the Multivibrator.*** For low frequency operation the stability of the multivibrator is poor because of the exponential nature of the discharge curve.

Multivibrators may be stabilized by returning the grids to the supply voltage. This in effect raises the discharge point by the amount of the supply voltage. A more linear portion of the curve can be used. A multivibrator circuit used in apparent motion research is given in Figure 7.8. This circuit uses 6AN8 pentode-triode tubes. The triodes are used as multivibrators. The pentode sections are used as grounded grid DC amplifiers which couple the 6BX7's to the multivibrator. The constants are chosen to give frequencies ranging from 2 to 10 cycles per second. The ganged potentiometers are the frequency controls. The instrument can be calibrated by adjusting Rcal.

7.12. ***Flipflop Circuits.*** The flipflop circuit is a monostable circuit which is sometimes called the Eccles-Jordan, after its inventors. It has two stable states and will remain in either until a) it is triggered or b) plate current is interrupted, in which case there is no guarantee as to which tube will conduct.

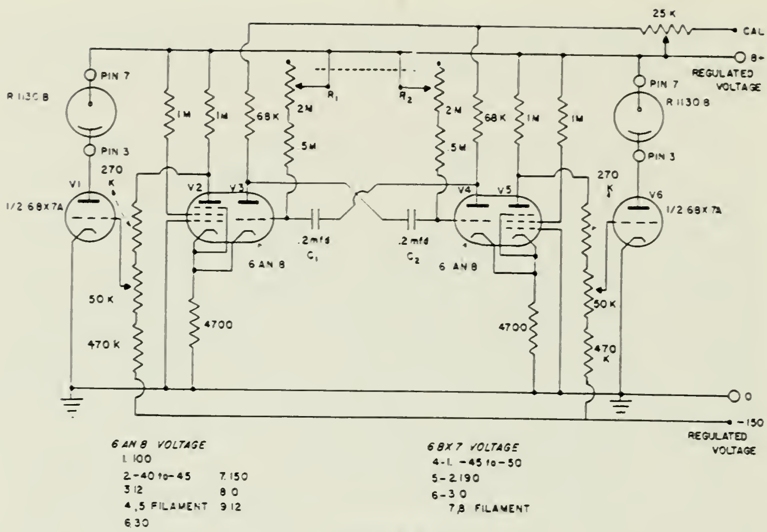


FIG. 7.8

The flipflop is also a binary or scale-of-two counter, since it can be designed to give 1 output pulse for each 2 input pulses. Chains of flipflops will then divide by powers of 2 as far as is desired.

A basic flipflop circuit is shown in Figure 7.9. This circuit can be triggered only by negative pulses. Since the output can be connected to the input of another flipflop without amplifiers or coupling diodes this circuit can be used as an element in simple frequency division by any power of 2 desired. We have used it to count down an oscillator running at a frequency of 20 to 100 cycles per second. Two scalers bring the output down to the 5-20 cycles per second range and four scalers will bring it down to the 1.25-6.25 cycles per second range.

The operation is similar to the multivibrator except that the two tubes are directly connected. We may consider that when voltage is applied, either tube may begin to conduct. If the right hand tube conducts, the plate potential and hence the potential at the grid of the left hand tube will fall. The plate potential of the left hand tube and the grid potential of the right hand tube will rise. This action in regenerative and ends with one tube conducting heavily and the other nearly cut off. In the circuit shown the voltage differential is about 60 volts.

The flipflop circuit can be incorporated in decimal as well as binary counters. This is discussed in Crufts (7) rather thoroughly. In fact, ring circuits can be designed to scale by any number. Such rings can be used as electronic stepping relays or ratchets.

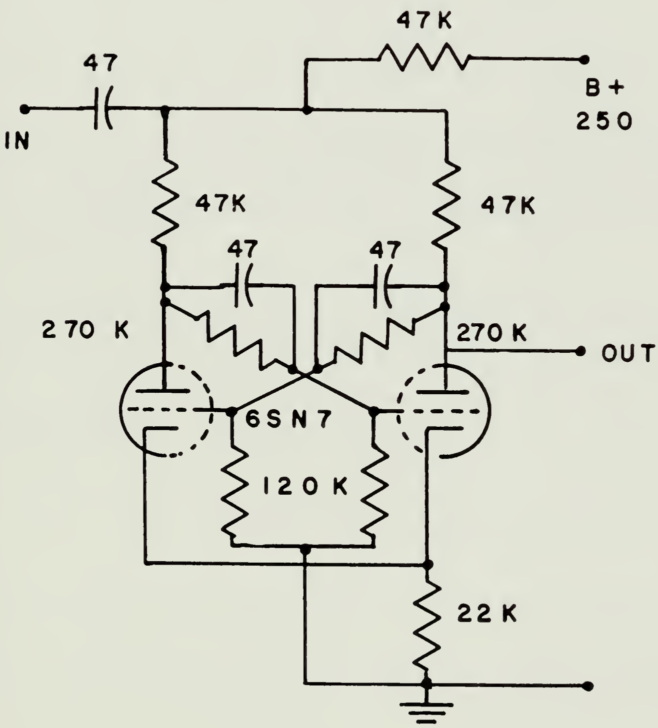


Fig. 7.9

7.13. *Schmidt Circuits.* The Schmidt circuit is a monostable circuit which holds one state but can be held in the other state by application of DC potentials. This circuit is useful as an amplitude comparator or for initiating action at some point on the slope of a complex wave form.

A circuit in use in our laboratory is shown in Figure 7.10. The circuit was designed to quantitize respiration and muscular movement. It can be seen that when V_2 is conducting cathode bias is applied to V_1. The plate of V_1 is kept near supply potential, but will fall when DC is applied to the grid. The grid of V_2 also drops, lowering

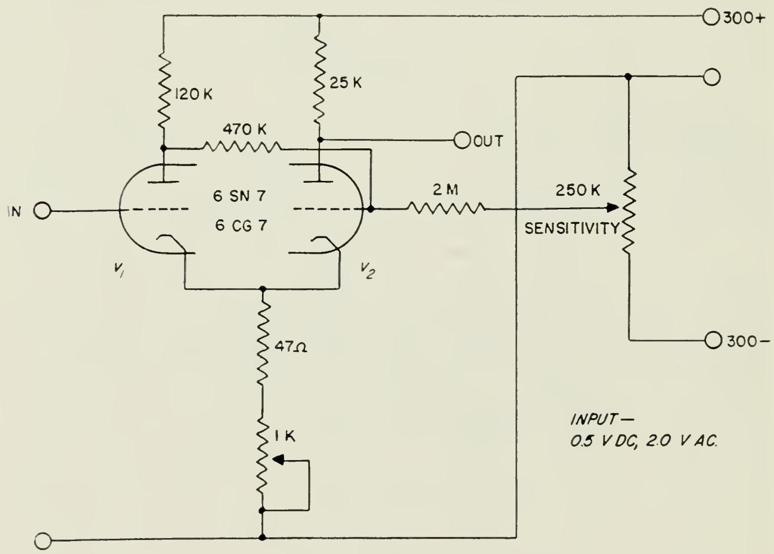


FIG. 7.10

the cathode bias on V_1 until the tubes suddenly exchange functions. When the grid input is removed they revert to their former states. These ciruits are discussed in detail by Dickensen (5).

7.14. ***Glow Counter Tubes.*** Glow counter tubes are gas tubes which count decimally. They are manufactured by Ferranti and by Sylvania. A tube consists of 10 triads of cathodes and a disc shaped plate. With a high resistance in the plate the most negative cathode conducts. When a cathode is conducting a small glowing spot of ionized gas appears at the cathode. Since these cathodes are arranged in a ring, they can indicate the number of pulses which has moved the spot from zero.

The discharge can be "handed" from cathode to cathode by applying negative pulses in serial order. The associated circuitry is quite simple. A glow counter decade ordinarily requires a twin triode such as a 6J6 for a driver as opposed to the 10 twin triodes required for a hard tube decade.

We have not used these tubes in laboratory equipment at this time. We have found, however, that Sylvania has been quite prompt in providing complete design data for their entire line.

It is worth noting that several companies, including Westport Electric manufacture time interval meters and batch counters using these tubes. We have found that the Westport Model WE-210 is an excellent piece of equipment. It will count events up to 9,999 or will time events to .0001 seconds plus or minus 1/10,000th part of a second. It has been used to calibrate squarewave generators used in visual research, to time thyratron control circuits, measure relay lag and for a host of other applications.

7.15. ***Summary.*** There are other time base generators available to the experimenter. A few elementary circuits have been discussed here, but by using these circuits it is possible to time most of the operations ordinarily arising in the laboratory. All of the circuits given here have been tested and used in experimental work. They work well without critical adjustments. It is worth noting, however, that where timing is critical to the experiment a time standard is required. It is our feeling that a counter circuit combined with an accurate crystal controlled oscillator is a wise choice, since it will provide markers for oscilliscope traces as well as time events.

Chapter 8

TIMED SEQUENCES AND SWITCHING CIRCUITS

8.1. ***Introduction.*** This chapter will deal with the characteristics and modes of operation of various types of switching devices. Electronic switching circuits have already been discussed in Chapter VII. In addition, there will be a brief discussion of the complicated type of circuitry found in computers and "thinking" machines. It will be seen that these simple elements may be so combined that they form interactive, mutually exclusive or complementary configurations by which it is possible to count a series, divide into sub-multiples or provide precise time durations from milliseconds to minutes.

It is necessary to begin with a description of the mechanical and electrical characteristics of commercially-available switch and relay components.

8.2. ***Switches.*** All switches perform the same types of operations; they allow a circuit or circuits to be interrupted, connected, or interconnected. The many types available commercially differ in their size, their mechanical means for operation and the number of circuits which may be controlled simultaneously. Almost any kind of mechanical motion may be employed to operate a switch, to name a few, pushing, turning, bending, tilting. Almost any combination of "on" and "off" arrangements are possible. It is therefore necessary to list the common types. Standard abbreviations will be employed in the definitions beneath:

Pole: Number of circuits which may be turned "on" or "off" by the switch operation, e.g.; SP, single pole; DP, double pole; 3P, triple pole, etc.

Throw: The number of positions available on a switch, i.e., the number of different connections available for the switched circuits, e.g.; ST, single throw; DT, double throw; 3T, triple throw, etc.

Gang: Synonymous with "Pole" except used for rotary switches.

Position: Synonymous with "Throw" except used for rotary switches.

Armature: The portion of the switch which is transferred from one circuit or position to another bv switch action.

There are seven basic types of switches commercially available. The following list is of basic types although other arrangements are possible, e.g., a microswitch may be mounted so that a motor driven cam can actuate it and the combination may be termed a "timer switch."

Toggle Switches: Switching is accomplished by manual operation. Available in combinations from SPST to 3PDT. Special versions are available with "dead center" where all circuits are open, or with a spring return to center off after operation.

Slide Switches: Switching is accomplished by linear displacement of the control button. These are usually small in size, available from SPST to 4PDT and are used to control small currents. "Dead center" versions are available.

Push Button Switches: Switching is accomplished by pressure on control button. Available only in SPST but in normally open (NO) and normally closed (NC) versions,

Microswitches: Switching is accomplished by pressure on control button or arm. Characterized by extremely short limits of travel (.020 inches), positive action. Available in SPST, NO and NC, also SPDT. Usually operated by cams or levers.

Rotary Switches: Switching is accomplished by rotation of control shaft, usually 30 degrees. Available in combinations from single gang, 2 position to 10 gang, 11 position. Usually require considerable torque for operation.

Mercury Switches: Switching accomplished by rotary tilt of element (usually 15 degrees). Has the advantage of being completely noiseless and is positive in action but is subject to jarring and erratic operation.

Thermal Switches: Used for time delay before "on" or "off" cycle. Switching accomplished by the thermal displacement of a bimetal strip. Unit mounted in a regular tube envelope with an octal socket. Available in fixed time intervals, both NO and NC, SPST arrangement only, with 6.3 or 115 VAC heaters. Time delay begins with passage of current thru heaters.

8.3. *Relay Types.* A relay is essentially an electromagnetically operated switch. In its simplest form it consists of an electro-magnet and a moveable armature bearing isolated contacts. The armature is moved from one set of fixed contacts to another by the passage of current thru the coil. It is therefore a switch capable of being operated at a distance. Relays are also capable of operating speeds far in excess of mechanical switches to speeds as high as 500 cycles per second for special types. Relays may be obtained in configurations from SPST to 4PDT while special telephone types are available up to 50PDT.

Since the switching operation of a relay is accomplished by potential applied to its coil, and since the switched contacts are electrically isolated from the control circuit, it forms a type of output transducer in some of the electronic switching circuits discussed in preceding chapters. A relay may be made to control other relays. In this sense, it is highly analogous in operation to the neural cell.

Of the wide variety of relay types available, the most important are listed beneath:

Spring Return Relays: The relay armature is positioned by means of a spring so that one set of contacts is usually closed. Application of potential to the coil causes armature motion against spring tension and the closure of the opposing set of contacts for the duration of the potential.

Stepping Relays: The relay armature does not bear switching contacts but causes a fixed angular displacement of a rotary armature. Successive pulses to the coil cause these successive rotary displacements thru 360 degrees with as many as 40 contact points. A special version of this type of relay has a rotary spring return automatically energized by the armature at its extreme excursion to return it to an initial or starting position.

Sensitive Relays: A specialized version of the common relay which because of mechanical and electrical design factors may be made to operate with as little as 90 microwatts of power to the coil (.035 volts at .0026 amperes).

Polarized Relays: Often termed "null seeking". A relay with a single armature and two coils facing and opposing each other. The armature is usually spring positioned between the two coils and sets of contacts. If one coil is energized with a specific potential at a particular polarity, a slightly greater potential of opposite polarity across the other coil is required for switching to the opposing contacts.

Polarized Relay: (Magnetic Latch-In): A specialized version of the polarized relay in which the armature is spring loaded to maintain either one of two stable positions. The application of one polarity of potential to the coil will cause the armature to transfer from a given fixed position to another. Opposite polarity is required to transfer it to the original position.

While the above is a listing of most common current types, new models are appearing rapidly. The design trend seems to be towards miniaturization, increased ruggedness and speed of operation.

8.4. ***Relay Applications.*** A relay of suitable coil resistance may be used as a plate load in many types of electron tube circuits where it is desirable to cause operation at certain peak values of tube output. The relay may therefore be used in the numerous types of multivibrator circuits for timing or switching purposes, in photocell amplifier autputs to indicate certain values of light input,

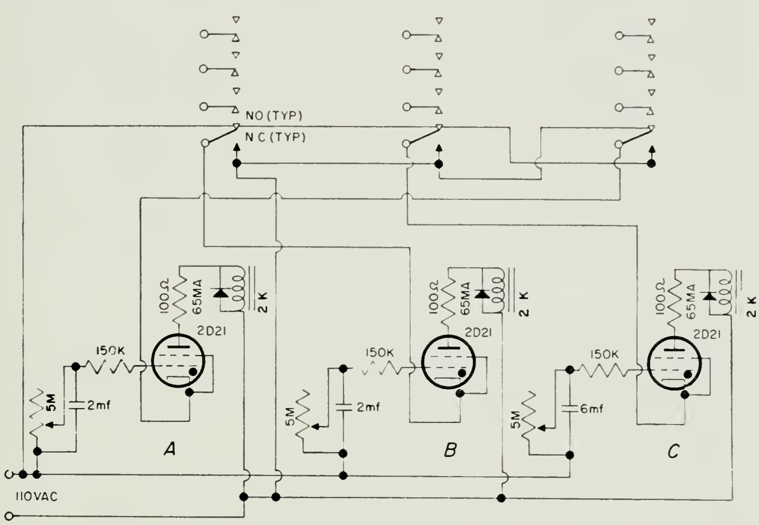


Fig. 8.1

etc. A thyratron-relay circuit is a "natural" configuration since the thyratron action is an "all-or-none" action similar to that of the relay. The circuit of Figure 8.1 utilizes the basic regularity of a condenser discharge curve and a simple "chain" of relays to provide for the timed, repetitive presentation of two or four sets of stimuli.

The general principle of operation is that of a number of variable timer units made to interact so that the operation of one triggers the timing cycle of an adjacent unit.

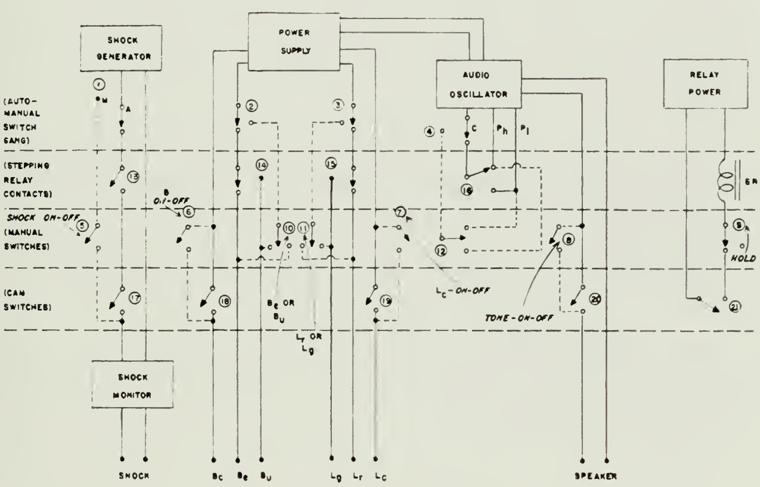
Unit operation is as follows: Assume that the resting position of the relay in unit "A" is such that cathode and #2 grid are connected to one side of the AC line while the #1 grid is connected to the other. The #1 grid now acts like a diode plate and a charge is built up on the grid circuit condenser. Now if the cathode and #2 grid are switched to the opposite side of the line, the high negative bias on the #1 or control grid begins to dissipate in the variable resistor. After a time delay depending upon the product of the condenser and variable resistor, the grid bias reaches the point where the tube and its associated relay fires. This changes the operating conditions of unit "B" so that it begins its timed cycle and, when B fires, unit "C" begins its timed cycle. When C unit fires, units A and B return to their original state and the process repeats itself. Each unit may be set for a different time delay but all units will be cut off when the last unit fires.

The line from the last to the first units is an actual feedback line, returning output to input. This is a positive type of feedback so that the whole assembly is maintained in continuous oscillation.

The remaining contacts of each relay may be used to control the desired stimuli, consequently at least DPDT relays should be used.

If the last unit in the chain is made to operate a stepping relay, this relay may be made to select one and another of two sets of different stimuli. For example, it is possible to present a five second red light followed by a one second shock, to insert a two minute delay, and then present a five second green light without shock. This alternation of stimuli may be repeated indefinitely. The times of each operation above is controlled by the setting of the variable resistor and are merely illustrative.

Any number of units may be interconnected so as to provide the required number of operations.



CONDITIONAL REFLEX CONSOLE

FIG. 8.2

If this basic timing unit is incorporated in the switching arrangement shown in Figure 8.2 above, this unit may be used as a "universal" conditional control device.

Provisions have been made for automatic or manual presentation of buzzer-bell, red-green light, shock-no shock conbinations for preset intervals, alternated regularly from one to the other of the stimulus pairs. Provisions have also been made for manual operation of all stimuli, for a "disabling" circuit which permits the continued presentation of whichever of the stimulus pairs were presented last, and a "changeover" switch, which permits the unit to be changed from one to the other of these pairs at any time during automatic presentation.

8.5. ***Relay Algebra.*** The simple switching operations performed by a relay are compounded in telephone switchboards and computers into elaborate circuits which are capable of certain types of logical operations. Only a brief discussion of this type of circuit will be presented since instrumentation for behavioral research usually does not require it.

In the circuits presented beneath, the common or return line has been omitted in most of the illustrations for simplicity.

Another convention is that the signal input will be shown as "I" and the output as "O."

The simplest relay operation is that of addition. This may be expressed, "if O, then A *and* B." This circuit is illustrated in Figure 8.3.

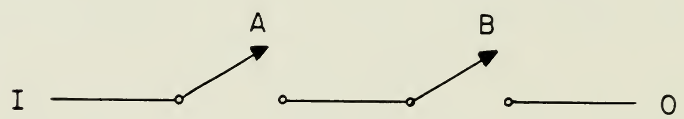


Fig. 8.3

Note that the closure of both A and B is necessary for the transmission of information from I to O and that neither condition alone is adequate. This type of circuit is found, for example, in coincidence counters where the noise or random signal level is likely to be high. If A and B are controlled by two separate circuits, each monitoring the same signal, random noise which does not appear simultaneously in both A and B circuits is cancelled out, while signals which occur simultaneously emerge at O.

The circuit of Figure 8.4 is a simple case of an "or" operation.

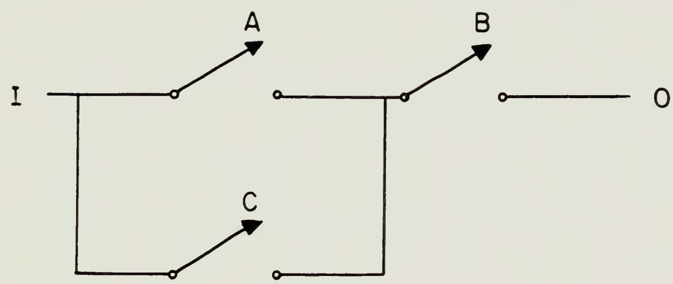


Fig. 8.4

Its operation may be expressed, "either A *or* C *and* B yields O." From the appearance of O, however, it is not possible to determine if action of A or C occurred. The

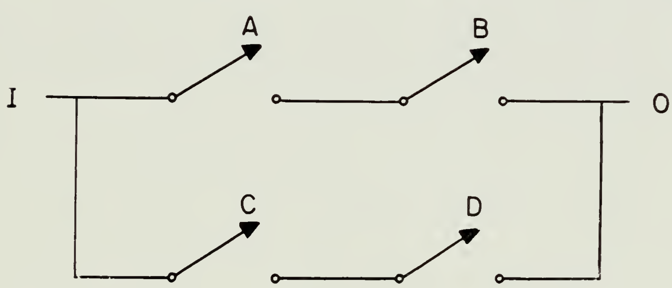


Fig. 8.5

closure of B is the only certain antecedant of O. This circuit appears in Figure 8.2 as an "override" circuit.

A double alternative, double coincidence configuration is shown in Figure 8.5 above.

Its operation may be expressed as, "either A or C and B or D yields O." Again it is not possible to determine from the appearance of a signal at O which members of the AC, BD pairs contributed.

In each of the above configurations, the relays had only two states, "open" or "closed." The use of a polarized or double throw relay extends the utility and flexibility of these networks.

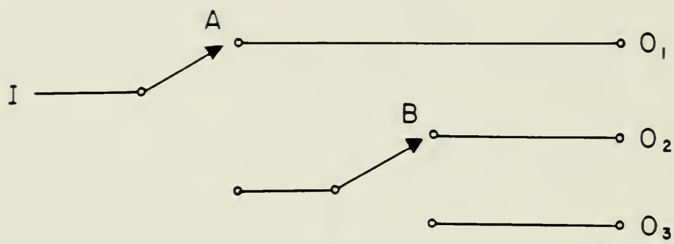


FIG. 8.6

Consider the simple "and" circuit of Figure 8.3 constructed with polarized double-throw relays as shown in Figure 8.6.

There are now three possible outputs for each of which the specific situations of both A and B may be determined.

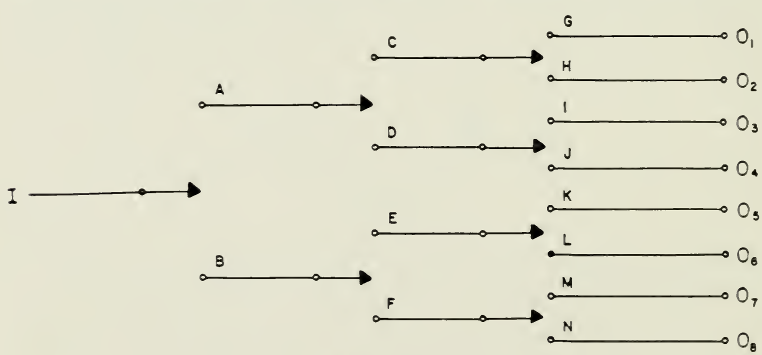


FIG. 8.7

Four sources of information could be combined or analyzed for coincidence with this circuit. The use of greater numbers of contacts would provide similar elaborations of the circuits illustrated.

The last illustration to be shown of this type of circuit is a simple replica of a vastly more complicated arrangement used in actual practice. This is the relay "tree" shown in Figure 8.7.

Each relay is polarized, and has two possible closure conditions. There are now eight different types of output information relating to a specific set of input conditions. For example, a signal at O_4 would indicate immediately that: I is closed to A, A is closed to D, D is closed to J.

Chapter 9

STIMULUS GENERATORS AND INPUT TRANSDUCERS

9.1. ***Definitions.*** In the broadest sense the basic principle of research instrumentation in the behavioral sciences is that of implementing the limited sensory resources of the observer. The detection, recording and measurement of responses of living systems involves phenomena which are truly imperceptible to the observer. Responses such as the electrical impulses arising from cortex or muscle or the subtle chemical changes in complex organic compounds acompanying emotional arousal are phenomena for which the human observer has no specific sensory receptor. Even when the overt and observable responses are of central interest; movement, temperature, rate of activity, the raw perceived response is generally unsuited as data simply because it is not readily quantifiable.

The production of stimuli for experimental purposes poses many of the same problems. Without the use of instrumentation the experimenter would find it very difficult to control with sufficient accuracy the qualitative and quantative aspects of the stimulus.

Instruments are therefore used to present stimuli, to detect responses, to modify these detected responses in some specific way (usually by amplification) and to produce a permanent or semipermanent record of the original information. The generic term for the portions of the instrument which either detect or record is "transducer," usually specified as "input" or "output" transducer.

The input transducer is some device which transforms the response of the organism into an electrical or mechanical analog. The output tranducer retranslates this analog into some perceptible and often, permanent record.

A familiar illustration of the typical instrumental system is that of the public address amplifier. The microphone (input transducer) converts varying sound pressures into varying electrical potentials, passes them to the amplifier for a multiplication of their amplitudes, and the loud speaker (output transducer) converts the electrical potentials back to sound pressures.

The quality of this system is judged in terms of the sensitivity of the input transducer, the fidelity of the amplification, and the efficiency of conversion of electrical to sound energies. The research instrument may be judged on the same basis; input sensitivity, fidelity of amplification and efficiency and fidelity of display. Both systems must have the additional characteristic of a high "signal-to-noise ratio," a convenient way of stating that they must be maximally sensitive to the phenomena for which they were designed and minimally sensitive to all other phenomena.

This chapter will deal with a variety of stimulus generators and the common types of input transducers. The succeeding chapter will deal with the most popular types of output transducers.

9.2. ***Requisites of Stimulus Generators.*** The output of a stimulus generator must be controlled, i.e., it must be specified in terms of an optimum number of relevant parameters. When the stimulus is electrical, for example, the most relevant parameters are voltage, current, temporal duration and waveform. Second, the stimulus generator must produce the specified stimulus only. An auditory generator must not produce light or any other stimulus not specified by the experimenter. The third requisite is that the output must be calibrated in units relevant to the receptor organ for which it is intended. It would not be appropriate to calibrate an auditory generator in terms of the number of volts appearing across the output unless something is known about the relationship of this variable to apparent loudness.

9.3. ***Auditory Stimuli.*** Auditory generators may be as simple or as complex as the experiment requires. Pavlov employed the sound of a buzzer, bubbling water, a metronome and a pure tone. For most purposes, the simplest device is the sound of a bell, buzzer or automobile horn. For pure tones, variable in pitch, a variable frequency oscillator connected thru an amplifier to a speaker or headphones is usually satisfactory. Most oscillators are variable in pitch thru a third or fourth of the auditory spectrum and then must be switched to a higher or lower range. The beat frequency oscillator (BFO) is available commercially in a model which may be swept continuously from one extreme of the audio range to the other without bandswitching and a motor drive may be purchased which will perform this automatically.

The least expensive audio oscillator may be purchased as a "code practice" oscillator from radio supply houses and provides two or three tones of fixed pitch and variable intensity.

For very precise work, where either pitch or volume must be accurately controlled, it is most practical to use a clinical audiometer.

The use of a magnetic tape recorder for complex sequences of auditory stimuli provides a means for the automatic timing of the stimulus presentation. The tape speed is quite constant and the stimulus sequences may be programmed in advance. Any other electrically controlled stimulus may be incorporated in this program by fixing gummed foil strips on the reverse side of the tape which will close a firing circuit for the additional stimulus. In passing, it may be noted that the magnetic tape recorder is preferable to the wire recorder with respect to fidelity, ease of operation and sensitivity.

"Delayed" auditory stimuli, usually employing the subject's own speech, amplified and fed back a fraction of a second later, may be produced by using a duplicate playback head on a tape recorder which is mounted "downstream" on the tape. The amount of delay may be controlled by varying the separation of the two playback heads, the tape speed, or both. The additional head is connected to an auxiliary amplifier, the output of which is mixed before being introduced into the subject's headphones.

Synthetic tones may be produced by using a rotating shutter between a steady light source and a photocell input connected to an amplifier and speaker. Varying the shape of the light source or the shutter aperture will produce tones of different waveforms while the pitch is modified by changing the speed of the rotating shutter. A considerable portion of the autitory spectrum may be swept without bandswitching in this manner.

The quality of amplifier and reproducer used in auditory stimulators must be high. Headphones, particularly the piezo-electric types, offer excellent reproduction at all but the lowest frequencies. When freedom of movement of the subject is desired, a speaker enclosure of the "infinite baffle" type is probably the simplest arrangement. Details on this and other speaker systems are available in the popular "hi-fi" literature. The most economical high-quality amplifier is available in kit form from Heathkit Company, Benton Harbor, Michigan.

9.4. ***Visual Stimuli.*** The simplest apparatus for the timed presentation of visual stimuli is the 35 mm slide or strip film projector. These are available with camera-type shutters with speeds from a full second to .01 second and with an iris diaphragm for controlling the intensity of illumination. The stimuli may be photographed in black and white or color in the desired sequences. A number of manufacturers offer strip film projectors with provision for manual or automatic sequence projection. Recently, Revere Camera has introduced a 35 mm slide projector with magazine loading and automatic projection of a sequence of several dozen slides.

One of the shortcomings of the use of slide projectors with mechanical shutters is that of the difficulty in getting brief exposures, particularly when stimuli must be presented at durations about the visual threshold. The standard projector may be modified to include a glow-discharge tube in place of the incandescent lamp. This tube is capable of almost instantaneous ignition and extinction and some provide an approximately pure white light output. The trigger circuit is shown in Figure 9.1.

This circuit is basically a monostable multivibrator discussed in Chapter 7. The duration of the flash is a product of R and C while the intensity of illumination is controlled by the value of variable resistor R. The tube originally employed in this circuit is the Amglo 50C5 although others are available from the same manufacturer.

The same general type of tube may be used for producing repetitive flashes at controllable rates for applications such as stroboscopes, photic driving, etc. This circuit is shown in Figure 9.2. A thyratron oscillator provides a variable train of pulses which fire into the primary of an ignition transformer. The tube, a Sylvania FT-110

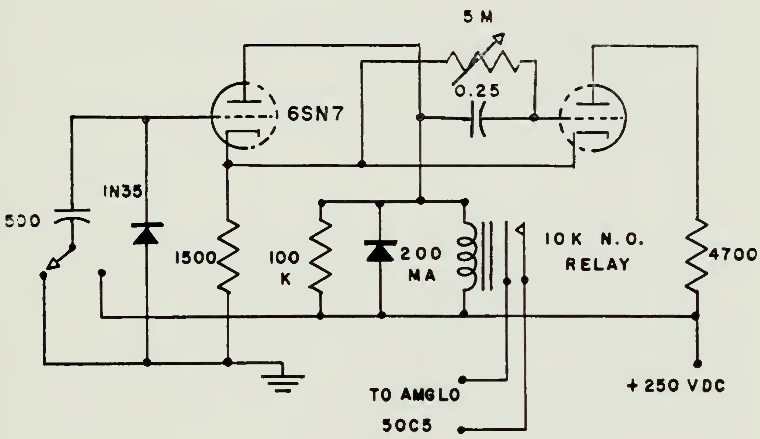


Fig. 9.1

or equivalent, carries a high voltage across it but will not fire until the gas in the tube has been ionized by the passage of a 10 kilovolt pulse into the ignition terminal of the lamp. At this time the full potential breaks the gas down in the tube producing a brilliant white flash of light. The storage condenser is exhausted very rapidly and must recharge before another flash can take place. The highest frequency obtainable is approximately 45 flashes/second.

Some investigations, particularly those dealing with the perception of apparent motion, require that a pair of lights be alternately illuminated and dark. The repetition rate, the frequency with which one lamp succeeds the other in illumination, should be variable. Such a circuit is discussed in Chapter VII, Figure 7.8. It employs a type of glow discharge tube originally developed for photo-facsimile use, the Sylvania R1130B. This tube is of the dimensions of an ordinary radio tube, contains a mixture of

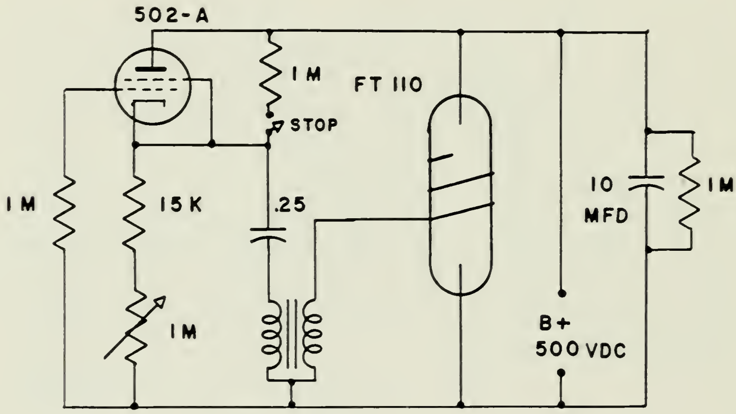


Fig. 9.2

rare gases and produces a vivid spot of light approximately .1 inches in diameter when viewed head on. The brightness level is quite high, the color approximates white and the switching rate ranges up to 15 kilocycles per second. The lights may be made any color by the introduction of Wratten filters.

It must be noted that incandescent lamps are generally unsuited for instruments requiring brief pulses of light of a "square" waveform. The thermal lag of the filament on both "on" and "off" cycles makes brief pulses assume a sinusoidal illumination curve and even shorter pulses may not produce any illumination. The use of shutters for brief pulses of light duplicates this type of error.

9.5. *Vestibular Stimulation.* This rarely-used stimulus may be produced crudely by injecting cold water into the ear canal. It may also be produced by rapid rotation of the subject but this method is also unsatisfactory. Vestibular stimulation is most easily produced by electrical means. Gauze-wrapped silver electrodes may be soaked in saline solution and introduced into the external auditory meatus. The stimulus is a DC pulse of approximately 45 volts obtained from a switch and battery circuit.

Pulsating direct current of variable frequency may be used by employing one of the stimulator circuits shown in Chapter 7.

9.6. *Tactual Stimulation.* Tactual stimulation is most easily accomplished by a device employing a magnetic type phonograph *recording* head. The head is suitably suspended in a fixture over the area to be stimulated and the desired type of stimulating element (blunt, sharp, etc.) clamped in the place of the needle. This head may be supplied from the output of an audio amplifier which is fed with signals of the desired frequency and duration obtained from an oscillator. Direct currents will produce a stimulus only at make and break. The amount of motion of the stimulating element is quite limited but is adequate for most experimental purposes. The piezo-electric type of phono reproducing head may be used in the same fashion but will give stimuli of even smaller amplitude, may not be used with direct currents and may be ruptured by excessive potentials. Either arrangement is capable of considerable power output despite the mechanical impedance of the stimulated area.

9.7. *Painful Stimulation.* While a wide variety of methods for producing painful stimuli have been reported in the literature, the two means most frequently employed are thermal and electrical. Thermal pain apparatus employs a high wattage incandescent lamp, mounted in a housing with suitable lenses to produce a concentrated spot of light and heat on the subject's skin. A shutter interposed in the light beam controls the duration of the stimulus while a variable transformer in the lamp circuit provides a control of heat intensity. The area stimulated in humans is usually that of the forehead and the skin is blackened to enhance heat absorption.

While this method is widely used, it is inherently clumsy and subject to artifact. Error is introduced by the variable thickness of subcutaneous tissue, by the presence or absence of perspiration on the skin, by environmental temperature, climatic factors, etc.

It is the opinion of the authors that electrical methods of painful stimulation provide a much greater degree of control over the parameters of the stimulus. The method is most frequently employed in animals as well as humans yet there has been relatively little attempt made to control the subject variables directly influencing the experience of pain. A brief discussion of these factors is relevant at this point.

Recent studies have related the experience of pain to the amount of electrical power dissipated by the subject. Since power is equal to the product of the square of the current x resistance, it is obvious that both factors must be controlled. Many studies indicate that a certain potential has been used but this is relatively meaningless unless the experimenter has simultaneously obtained the subject's resistance or has employed constant-current type stimulators.

It is possible to devise circuits which continuously monitor these parameters of the stimulus or which provide either constant voltage or constant current shocks. It is impossible to provide *both* constant current and constant voltage simultaneously because the former requires an infinitely high impedance source while the latter requires an infinitely low impedance source.

The simplest constant current generator consists of a source of *high* potential of from 300 to 1000 volts, either AC or DC, connected to the subject thru a high resistance in the order of tens of megohms. The resultant source impedance is thereby made high.

An equally simple constant voltage generator consists of a variable transformer (Variac) or a battery, directly connected to the subject. Thus the constant voltage generator has a low source impedance.

Unless one is using a DC stimulus, *the subject should always be isolated from the line* by means of a 1:1 ratio transformer, known as an isolation transformer. If this precaution is not taken, the full line voltage may be impressed across the subject as the result of an accidental ground connection. Such a shock could be fatal. An additional precaution in the design of shock circuits is that of the inclusion of a relatively low current fuse, not to exceed 1/200 ampere in *both* subject leads.

Condenser shock circuits offer some unique advantages in behavioral research investigations. The shocking current is delivered in what is experienced as a unit pulse of energy, practically constant current is insured by the very low impedance of the condenser, and finally, the residual charge on the condenser following the shock may be monitored to provide a measure of the power consumed by the subject during the shock. The total shock situation may thus be more controlled. A simple circuit with these features is found in Figure 9.3.

Switch S_1 may be a single pole, triple throw, spring return type or may be relay contacts actuated by a timing circuit, etc. The condenser is charged from the voltage divider between shocks and this charge is dumped into the subject during the shock cycle. The contacts are then returned to their third position where the residual charge may be read. A high impedance vacuum tube voltmeter must be used to monitor the remaining charge.

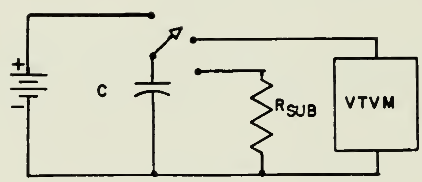
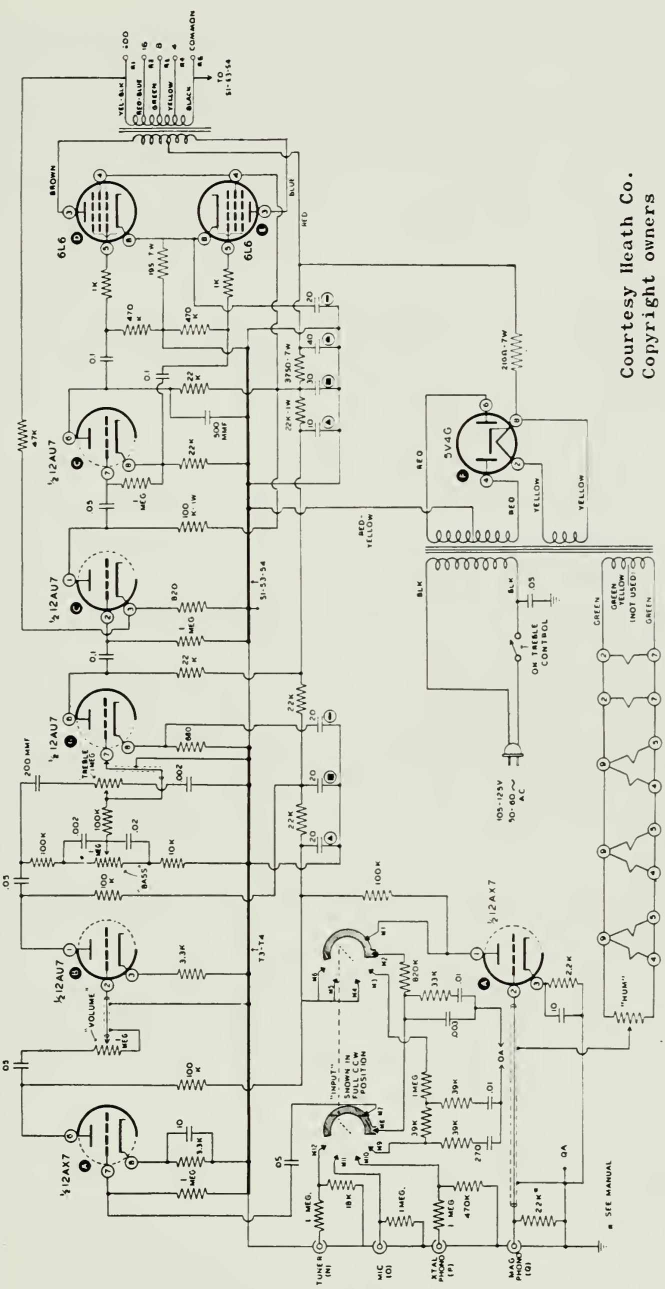


FIG. 9.3

Repetitive stimulation is most easily accomplished by the use of an oscillator circuit. RC or LC oscillators must be used for the generation of sinusoidal waveforms, and these are described in Chapter VII. A simple oscillator for the generation of non-sinusoidal forms is that of the blocking oscillator shown in Figure 11.9.

The operation of this oscillator is discussed in Chapter 11. The output waveform will consist of positive and negative spikes.

Practically any waveform may be used for shock purposes when it is used as an input for a suitable power amplifier. The amplifier should have low output impedance and considerable power gain besides the usual characteristices of freedom from distortion, linearity, etc. Such a circuit is shown in Figure 9.4.



Courtesy Heath Co.
Copyright owners

Fig. 9.4

The output appearing across the 500 ohm load resistor is practically a constant voltage source.

Numerous interesting experimental variations to faradic stimulation are made possible by the use of this circuit. Heart sounds, speech, or random noise may be amplified and used as a shock stimulus for the production of pain.

9.8. ***Olfactory and Gustatory Stimulation.*** The production of these stimuli represent difficult and elaborate instrumentation problems. It is the opinion of the authors that research in these areas has been limited by the lack of suitable stimulus generators.

For olfactory stimulation, the Zwaardemaker olfactometer or some variation is the most practical solution. Gustatory stimulation is best produced by the introduction of liquids upon the tongue.

Much instrumental research is needed in these areas.

9.9. ***Input Transducers.*** The input transducer is probably the single most important portion of the research instrument. Its design requires the utmost of engineering skill and ingenuity. It is a kind of gateway for behavioral information and only the information passing this gateway will ever be available as data.

Some general criteria may be set up for the evaluation of an input transducer.

1) The input transducer must be optimally sensitive to the response for which is has been designed and maximally insensitive to all other response. In simple terms, it must have a high signal-to-noise ratio.

2) The input transducer must produce a minimal amount of disturbance to the organic system to which it is applied.

3 The input transducer must not introduce distortion of the response which it transforms.

4) As a practical consideration, the input transducer must be as simple as the phenomena under investigation will allow.

5) Maintenance of the transducer must be simple and rapid.

9.10. ***Special Cardiac Tranducers.*** The standard methods of electrocardiography employ the simplest type of input transducer, a chrome plated or silver electrode fastened to the body. An electrode paste, usually a saline or other low resistance compound, is rubbed into the skin beneath the electrode.

For animal work, the electrodes may be made from hypodermic needles carefully soldered to cables. The cable or needle may be anchored to the hair by the use of collodion or low melting point wax compound.

For some research problems, cardiac frequency is the response of interest. Use of regular EKG equipment requires the tedious counting of waves. At least two commercial instruments are available which register metrically the beat-to-beat heart rate. Suppliers are the Waters Corporation and the Yellow Springs Instrument Company. The essential principle of their operation is that of measuring the charge (or discharge) rate of a condenser when it is charged (or discharged) intermittently by the amplified heart beat. Standard EKG electrodes are used and the rate may be recorded on a recording milliammeter such as the Model AW made by the Esterline-Angus Co.

Another device which provides a measure of cardiac waveform (as in the EKG) and an additional measure of "stroke volume," is the ballistocardiograph, manufactured by Technitrol. This is of particular interest as an illustration of a type of input transducer, the RCA 5734 electronic tube. This is a triode-type tube which is sensitive to minute mechanical displacements. The grid is mounted so that it is capable of a small plate-to-cathode excursion when a force is applied to its protruding end. In use, the tube is amplifying a small signal. The instrument consists of a steel table on which the subject reclines, suspended on stiff springs which allow a small amount of motion in a head-to-foot direction. At each heartbeat the force of the ejected blood, mainly against the aortic arch, produces a recoil of the reclining body which is transmitted to the table top. The tube is held in such a way that this force displaces the grid, creating an electrical signal which is further amplified and recorded. The main advantage of the instrument is the lack of encumbrance to the subject.

An inexpensive variation of this instrument may be made from a high-output piezo-electric phono cartridge. This is clamped to the ankle so that it is held horizontally with the needle chuck upwards and the long dimension of the cartridge at right angles to the head-foot dimension of the body. If a two ounce lead weight, mounted on an $1\frac{1}{2}$ inch stiff steel wire is clamped in the needle holder, the head-to-foot excursions of the reclining subject create a distortion of the crystal and an electrical output. This may be amplified and recorded. Such an arrangement is most suitable for recording cardiac rate.

When heart sounds are required as measures, a special cardiac microphone is available from Brush. This is an inertia type microphone which is maximally sensitive to mechanical displacement. The amplifier used in conjunction with this instrument must have a good low frequency response.

9.11. *Blood Pressure Tranducers.* These devices fall into two main types; those measuring occlusion pressures (the amount of external pressure required to collapse a blood vessel), and those measuring end-pressures (the internal pressure of the blood in the vessel). To date there are no adequate means for the continuous measurement of occlusion pressures. The simple manometer and cuff arrangement provides a "continuous-discrete" measurement which is adequate for some research purposes.

Ingenious but inadequate electronic devices have been designed for the continuous measurement of occlusion pressures. One such device uses an inflatable cuff, inflated quickly and deflated at a regular rate by mechanical means at regular intervals. Electromechanical transducers automatically monitor the radial pulse, a tracing of which appears beside a tracing of the cuff pressure. Systolic and diastolic pressures are read from the two tracings. Among the disadvantages of this device are the fact that they produce eventual ischemia, create an artifactual disturbance in circulation and are prone to multiple failures.

Relatively simple and sensitive devices are available for the measurement of end pressures. A strain gage transducer, manufactured by Statham, is available in two sensitivities; 0-5 mm Hg and 0-75 mm Hg. While simple and accurate, their use in human studies is limited. The artery must be cannulated and this creates disturbance, discomfort and danger to the subject as the result of potential clotting at the site of the cannula.

Their operation is relatively simple. A chamber in the transducer is filled with blood and sealed. Pressures in the system are transmitted via a flexible metallic diaphragm to a Wheatstone bridge made up of strain sensitive wire. The electrical resistance of this wire changes drastically with elongation. The bridge is so arranged so that positive or negative changes in pressure affect different pairs of arms of the bridge. The resultant output may be amplified and recorded.

9.12. ***Plethysmographic Tranducers.*** Plethysmography provides a measure of changes in the vasomotor tone in the extremities. Older methods used a fluid filled vessel

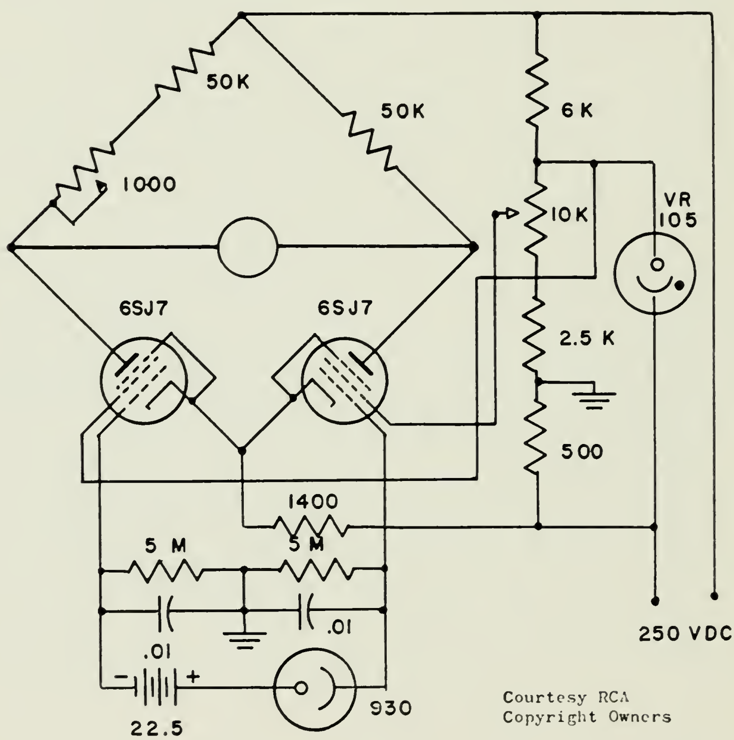


Fig. 9.5

in which the extremity was immersed and the amount of fluid displaced (after initial calibration) provided a means for assessing volume changes in the extremity. By a simple modification of the principle of the oximeter, it is possible to measure this response electronically. The circuit of Figure 9.5 is an illustration of this method.

A light source is held in intimate contact with the subject's fingertip. Directly beneath this and shielded from other illumination is a small cadmium sulfide photocell (Clairex C1-2). The output of the cell is led into a DC amplifier and recorder.

The amount of light reaching the cell is a function of the optical density of the fingertip which in turn depends upon its vasomotor state. The system is adequately sensitive to depict the temporary vasodilitation caused by a pulse wave as well as the gross density of the fingertip.

Great care must be used in the construction of a mechanical system for holding the light source, fingertip and photocell in juxtaposition. The cell must "see" only the light transmitted by the fingertip and the light may be led thru a solid Lucite rod so that heat from the lamp will not cause artifacts.

There are vacuum phototubes available from RCA which are suitable for this circuit due to their small size and high sensitivity.

9.13. *Respiration Transducers.* Traditional transducers for this purpose have consisted of a flexible rubber tube of accordian-fold design, closed at one end and strapped securely about the subject's chest. A pneumatic connection from the open end of the tube to a suitable mechanical recording system provided a record of breathing. The chief disadvantages of this system are its inability to detect shallow breathing and the delicacy of the recording system.

Very accurate measurements are made possible by the use of a type of manometer where the total volume of inspired and expired air is pneumatically recorded. Such an appliance creates considerable discomfort and consequent artifact.

Since the most important variable usually encountered is that of respiratory frequency, the circuit of Figure 9.6 has proven quite satisfactory.

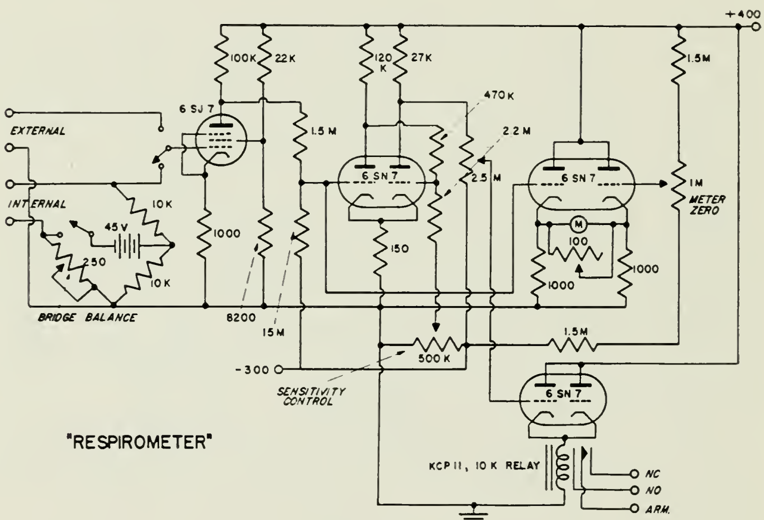


FIG. 9.6

The bridge input of this circuit contains an "unknown" resistance leg made up of the input transducer. This is a latex rubber tube firmly packed with carbon granules with metallic electrodes mounted in each end. This arrangement is strain sensitive, the resistance decreasing with elongation. The bridge output passes thru one stage of voltage amplification and an output at this point will provide a reasonably accurate reproduction of the respiratory curve. From the voltage amplifier, the signal is made to actuate a Schmidt trigger circuit, essentially a monostable multivibrator. Balancing the bridge after the transducer has been applied and setting the trigger point of the Schmidt will produce relay closure at any point on either the inspiration or expiration curve.

Circuits are available in the literature for integrating the respiratory cycle but these must be operated from other types of input transducers, particularly those of the variable capacitance type.

9.14. ***Heat Sensitive Transducers.*** The essential element in this type of transducer is the thermistor. The thermistor is a type of resistor, the resistance of which is a function of its temperature. A wide selection of thermistors, some of which are small enough to be placed in the bore of a hypodermic needle are available from Veco Corporation.

In use, the thermistor is placed in a Wheatstone bridge and the imbalance resulting from temperature change appears in electrical form at the output. This signal may be directly metered or amplified and recorded.

If it is necessary to measure the temperature of an organ relative to environmental temperature, two matched thermistors are used, one of which is placed in the experimental location while the other is placed in free air. The two thermistors appear as adjacent legs of the bridge. An imbalance results only from a difference between the temperatures of the two thermistors.

Two precautions should be taken in the construction of this type of instrument. The resistors used in the bridge should be of precision quality and a calibration resistor (representing the resistance of the thermistor at some standard temperature) should be provided which may be switched into the bridge to provide a reference value.

9.15. ***pH Transducers.*** Commercial apparatus is available from Beckman for the precise measurement of the relative acidity and alkalinity of body fluids such as saliva, urine, sweat, etc. While the electronic portions of such devices are relatively simple, special glass electrodes are required which may not be easily constructed.

9.16. ***Motion Transducers.*** Certain studies, for example those in the area of suggestibility, may require the precise measurement of the extent and direction of gross body movements. The circuit shown in Figure 9.7 beneath was designed to measure body sway.

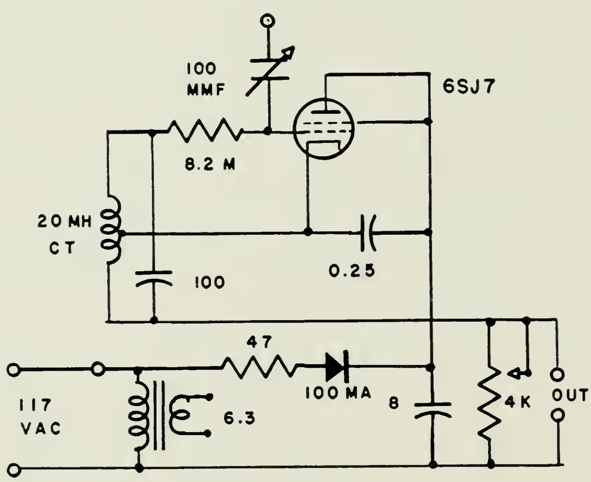


Fig. 9.7

This is essentially a 100 kc oscillator which is tuned to the point where it is ready to go out of oscillation. The capacity between the sensor element (the input transducer which may be a 6 foot copper wire standing vertically) and the subject serves to detune the oscillator and thereby cause more plate current to be drawn. The meter in the plate circuit serves to indicate sway and has an associated bucking circuit by means of which the subject may be "zeroed in" when placed in position. In setting up the circuit, C_1 should be tuned for maximum sensitivity and will not need additional tuning until a different sensor unit is used.

9.17. ***Eyeblink Transducers.*** The detection of eyelid closure is greatly simplified by the use of a phono cartridge as the input transducer. The cartridge is suspended on a firm headband in a horizontal position tangent to the skull and ahead of the ear. Its long axis should be parallel to the long axis of the skull. Linkage with the upper lid is accomplished by a tiny metal saddle soldered to a fine steel wire held in the needle chuck. The saddle is cemented lightly to the upper lid with collodion.

When properly constructed and applied, the device is scarcely perceptible to the subject and delivers almost a full volt output upon eyelid motion. This output may be amplified and recorded.

9.18. ***Muscle Action Transducers.*** The transducers used for this type of measurement are usually metal plates or needles located adjacent to or situated within muscle groups. The electrical potential accompanying muscle action is led thru conductors to a high gain AC amplifier such as an EKG or EEG amplifier.

9.19. ***Output Transducers: The Display and Recording of Signals.*** The final step in the handling of the biological signal is that of a reconversion of electrical energies back to some perceptible indication of their characteristics. This display may be momentary, the deflection of a meter needle across a dial or a tracing on the face of a cathode ray tube. The display may be permanent by employing some type of writing equipment which is displaced by the signal and so traces its characteristics on ordinary paper or photographic films moving beneath it at a controlled speed

The choice of metric (impermanent) or graphic (permanent) means of recording must be made on the basis of the specific requirements of the experiment. Where only one variable is to be measured, it may be convenient to employ metric displays since these are usually less complicated and expensive. Graphic recording is mandatory, however, where multiple variables are being observed, where brief or transient responses are anticipated, where temporal or amplitude relationships between two or more variables may be of interest, or simply when the experimenter's attentions are required elsewhere.

A brief discussion of the principles of operation of typical recording equipment may serve to indicate the further advantages and limitations of each type of recorder.

9.20. ***Meters and Recording Pen Motors.*** A meter is the simplest device for indicating electrical quantities. Meters are available commercially for the measurement of potential, current and frequency of both AC and DC. Basically their mechanisms are quite similar. It will be remembered that the motion of a coil of wire in a strong magnetic field produces a measureable current flow as the wires cut magnetic lines of force. If the reverse of this situation is produced by mounting a rotatable coil of wire in a magnetic field, the application of a current to the coil will produce a magnetic field within the coil. Since it is rotatable, the coil will quickly align itself so that its poles are proximal to, unlike poles of the field magnet. If the potential thru the coil is reversed, the rotation continues through 360 degrees. This is the basic principle of electric motors and of the electrical meter. The current or voltage fed into the meter produces a magnetic field about the meter coil which then rotates until this field and that of the permanent magnet surrounding it are in dynamic balance. In a meter, this coil is made to work against a spring, so that the amount of rotation is proportional to the magnitude of the electrical phenomena impressed. An indicating needle is fixed to the rotating coil.

Recording pens, such as those found in EEG inkwriters, are practically identical in structure with that of the meter. The field magnets are made much stronger and the coil is made larger with sturdier pivots. The needle is replaced with a hollow steel tube, serving as a pen. The power requirements of recording penmotors are considerably greater than those of meters.

While adequate for most measurement purposes, the meter-type movement is basically limited in its ability to respond to rapid changes in amplitude or polarity of input. Even the best pen motors tend to attentuate the signal at frequencies above 100 cycles per second. The inertia of the coil mass and pen tube tend to smooth out these frequencies.

The amplitude of excursion of a moving coil type mechanism is also limited. The one notable exception to this is the recording milliammeters made by Esterline-Angus which will provide almost six inches of useable trace. These meters are made in 0-1 and 0-5 milliampere sensitivities with a wide range of variable chart speeds.

9.21. ***Cathode Ray Tube Indicators.*** The cathode ray tube affords an excellent means for the metric display of phenomena, particularly of extremely brief signals. It is depicted in Figure 9.8.

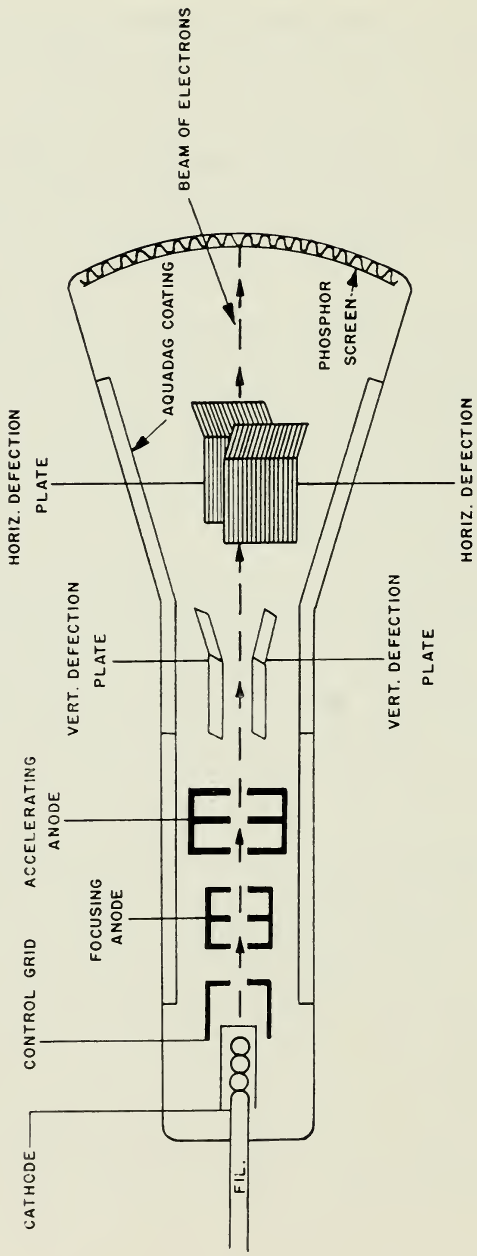

BEAM OF ELECTRONS
AQUADAG COATING
PHOSPHOR SCREEN
HORIZ. DEFECTION PLATE
HORIZ. DEFECTION PLATE
VERT. DEFECTION PLATE
VERT. DEFECTION PLATE
ACCELERATING ANODE
FOCUSING ANODE
CONTROL GRID
CATHODE
FIL.

Fig. 9.8

At the base of the tube is a cathode-electrode arrangement called a "gun" which projects a small, intense beam of electrons towards the face of the tube which is coated on the interior with substances which fluoresce when so activated. There is produced, consequently, a tiny spot of intense light called the "trace." Deflecting plates are located within the neck of the tube at 90 degree stations (right-left, up-down) which when appropriately charged, cause a corresponding deflection of the trace. Since the beam is made of negative charges, a positive charge on the upper plate and a negative charge on the lower plate will cause the beam to be displaced downwards on the tube face.

The degree of deflection will be proportional to the amount of charge appearing on the deflection plates. The charge is supplied by amplifiers within the instrument. The gain of both vertical and horizontal amplifiers is variable. Now if a sawtooth oscillator is connected to the horizontal input amplifier and there is no signal on the vertical amplifier, the beam will sweep steadily across the tube face as the wave builds up in a linear fashion. At the end of the sawtooth wave, the beam will return quite rapidly to its starting point. A special oscillator circuit is built into the instrument which interrupts the electron stream during this return sweep and this is known as a "blanking" circuit.

This sweep action is repetitive, constant and may be controlled in frequency from times as long as ten seconds to as brief as .003 seconds per trace.

If a signal of any frequency is applied to the vertical amplifier, the beam will be directed upwards and downwards as it sweeps steadily across the tube face, faithfully reproducing the potential variations of the input signal.

Since the electron beam is nearly without weight and inertia, the reproduction is almost perfectly accurate. Further, by speeding up the automatic horizontal sweep, the signal may be "spread out" in time; a signal of microsecond duration may be made to occupy the entire five inches of tube face.

The only limitation of the cathode ray tube system of display is that the trace is transient and must be photographed for permanent records.

The extreme flexibility of the CR scope is apparent after some use. Tubes are available with long or short persistance of the fluorescent coating, with various colors of fluorescence, and currently, with completely dual sets of elements so that two phenomena may be observed simultaneously.

Chapter 10

TEST INSTRUMENTS

10.1. *Introduction.* While it is possible to buy commercially built equipment to measure any and all of the parameters commonly encountered in instrumentation work, it is felt that a working knowledge of the design of instruments is of some value. One needs to know the limitations of measuring equipment and the possible errors introduced by equipment. There are times when it is feasible to build monitoring equipment into research equipment in order to free bench equipment for other uses. With this in mind, this chapter will be devoted in part to the evaluation of commercial equipment and in part to the principles upon which such equipment is based.

10.2. *D'Arsonval Meters.* The D'Arsonval or moving coil meter is a basic measuring instrument. If current is passed through a coil of wire in a magnetic field the wire will move because the interaction between the magnetic field around the wire and the field of the magnet represent an energy interchange. Poles of the steady magnetic field, usually supplied by a permanent magnet of Alnico or similar alloy, will oppose the poles of the field of the wire.

The rotation of the coil in Figure 10.1 will be in a direction determined by the direction of current flow through the coil. The amount of movement will be roughly proportionate to the intensity of the current. Further linearity is assured by the use of a hairspring coil.

Under these conditions the meter is an ohmic device in that rotation is in proportion to current flow. When the current in a circuit is known, voltage and resistance can be found by Ohm's Law if two of the quantities in the expression E = IR is known.

It is a DC device. It will not measure AC current because the average current would be zero. Moving vane meters are at times used to measure AC but they are non-linear and at times have poor frequency response. It is

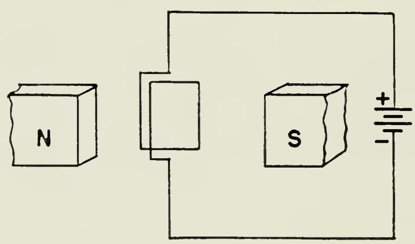


Fig. 10.1

in general a better practice to use a fullwave bridge rectifier and a DC meter movement to measure alternating current. If appropriate meter multipliers are used germanium diodes make excellent meter rectifiers.

Meter movements range from 10 microamperes to 10 or more amperes. Meters are also classified according to the circular size of the body of the meter if they are round or by case dimensions if rectangular. We have found that the most useful meters in the laboratory are the 0-1 milliampere movement, the 50 microampere movement and the 20 microampere movement. The 0-1 milliampere movement is less liable to damage from shock and movement. The other two meter movements can be made to read any reasonable current or voltage by appropriate multipliers or shunts.

10.3. ***Meter Multipliers.*** The resistance of an 0-1 milliampere meter is such that it will give full scale deflection if a 1 volt source is used in series with a 1000 ohm resistance. It is said to be a 1000 ohms per volt movement. It can be seen that potentials larger than 1 volt will cause excessive current to flow through the meter. For each additional volt an additional 1000 ohms must be added to the series resistor or multiplier. Ohms per volt for the most common meter movements are given in Table 10.1.

TABLE 10.1

RESISTANCE OF METER MOVEMENTS IN OHMS PER VOLT

0-1 Milliampere	1,000 ohms per volt
0-500 Microamperes	2,000 ohms per volt
0-200 Microamperes	5,000 ohms per volt
0-100 Microamperes	10,000 ohms per volt
0-50 Microamperes	20,000 ohms per volt
0-20 Microamperes	50,000 ohms per volt

To calculate the multiplier needed for a given voltage E, use the relationship $M = E/I$. This neglects the internal resistance of the meter but will cause no serious error unless the meter has an internal resistance which includes a multiplier. In that case the multiplier resistance must take into account the internal multiplier.

It can be seen that by using a basic meter movement almost any desired full scale voltage can be measured. The accuracy of measurement depends upon the accuracy of the meter, the accuracy of the multipliers and the total impedance of the meter and the multipliers. For example, a 20,000 ohms per volt meter will have an impedance of 4 megohms for full scale deflection at 200 volts, but this will impose a considerable load upon high impedance circuits. The voltage reading will be somewhat lower than its actual value. A 2,000 ohms per volt meter will present 200,000 ohms load across the circuit being measured.

10.4. ***Meter Shunts.*** When it is desired to use a basic movement to measure current higher than the full scale current of the meter, a parallel path must be provided so that only a part of the current will flow through the meter itself. This is called a meter shunt. It must be lower than the resistance of the meter movement. For example, if an 0-1 milliampere movement is to be used to measure a current of 1000 milliamperes, the shunt must carry 999/1000 of the total current while the meter movement carries only 1/1000 of the total current. The shunt resistance can be calculated by $R_s = R_m/N\text{-}1$ where R_s is the shunt resistance, R_m is the resistance of the meter and N is the factor by which the original scale is to be multiplied. The resistance of the meter cannot be derived from the ohms per volt factor. If the manufacturer's specifications are not available, the resistance can be measured by the scheme shown in Figure 10.2. Under no circumstances

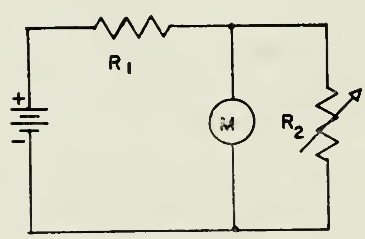


FIG. 10.2

should an ohmmeter be used for this measurement, since ohmmeter potential of 3 or 6 volts will seriously damage a sensitive meter movement. R_1 should be large enough to keep the meter below half scale when set at maximum. Adjust R_1 for full scale deflection and adjust R_2 for half scale deflection. R_2 is then equal to the resistance of the meter movement. The ohms per volt sensitivity can be found by dividing R_1 by E. Both these measurements may be of value when meters of unknown value are to be used in the laboratory.

10.5. *Ohmmeters.* Ohmmeters measure resistance and so are indispensible in the laboratory shop. Ordinary ohmmeters are based upon the circuit shown in Figure 10.3.

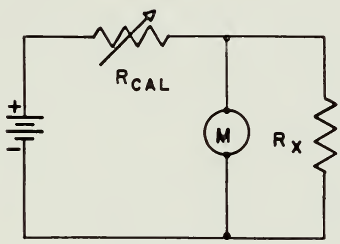


Fig. 10.3

The principle is that of measuring the current through a shunted resistor. The circuit is adjusted so that with no external resistance in shunt with R the meter reads full scale. A resistance equal to R will give a half scale reading. A resistor equal to 2R will give one third scale reading. It can be seen that such a scale will be exponential in nature.

10.6. *Multimeters.* All of the functions of a meter can be combined in one instrument called a multimeter. A sample commercial meter has 38 volt-ohm-milliampere scales and employs a 20,000 ohms per volt movement. The multimeter is a basic measuring instrument in the laboratory and in the shop. If the shop budget is small, we recommend the use of the excellent 20,000 ohms per volt kits supplied by Allied Radio, Heathkit and others. The Simpson line of multimeters are widely used and are to be recommended if commercially wired instruments are desired.

10.7. ***Voltohmmeters.*** The voltohmmeter is a vacuum tube circuit which will measure voltage and resistance but not current. Although its accuracy is not exceptionally high, the high input impedance and high resistance measurement capacity make the voltohmmeter the workhorse of the electronic laboratory. Commercial voltohmmeters have 11 or 22 megohm input impedance. Consequently they do not load most circuits when voltage measurements are being made. In the circuit shown in Figure 10.3 each tube is actually an element in a bridge circuit. The grid of V_2 provides a reference for the system.

A DC voltage on the grid of V_1 unbalances the system by causing current to flow through V_1. Since the cathode of V_1 is at a higher potential than the cathode of V_2, current

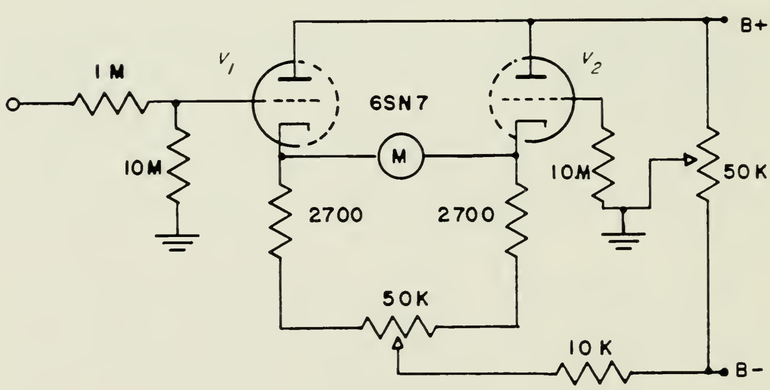


Fig. 10.4

will flow through the meter movement. In commercial models an ohmmeter and a rectifier are added. It has been our experience that kit instruments are entirely adequate for most purposes, but numerous commercial instruments are available for less than $100. The RCA Voltohmyst is an exceptionally stable instrument.

10.8. *AC Voltmeters.* An AC voltmeter is essentially a calibrated AC amplifier which feeds a rectifier. The rectified AC is then measured by a DC meter movement. Whereas the ordinary vacuum tube voltmeter measures AC in volts, AC voltmeters will make accurate measurements in the millivolt range and have a wide frequency response range. A kit instrument is supplied by Heath. For serious research in auditory stimuli the Hewlett-Packard audio voltmeter is highly recommended. It is quite stable and accurate and has a very low hum level.

10.9. *Readout Meters.* Where the increased cost can be justified, meters which read out digitally or print out can be purchased. Several companies manufacture these meters. Since we have not used them in our work we do not feel that we are qualified to make recommendations concerning any particular circuit or model, but it should be noted that such instruments are available. It is our understanding that they were developed for production line work in the electronics industry but are being made available for over-the-counter sales at this time.

10.10. *Oscilloscopes.* The cathode ray tube is discussed in Chapter 9. There is little doubt that the oscilliscope is one of the most valuable of all electronics tools for both behavioral research and instrument design. A good oscilloscope is a basic instrument for the laboratory shop. We believe that such an instrument should have the following specifications:

1. Long persistence screen such as the P-7, which has a fast blue trace and a slow yellow trace. Either can be enhanced by the use of proper filters.

2. Calibrated sweep times from 10 microseconds to 10 seconds per sweep. The sweeps should be repetitive or triggered.

3. Broadband video amplifiers for both horizontal and vertical inputs. Bandwidth should be DC-5 megacycles.

4. Retrace blanking or triggered unblanking.

5. A 3 inch screen or preferably a 5 inch screen.

The Hewlett-Packard Model 130A-7 or Tektronix 315D are portable oscilloscopes which meet these requirements. These instruments are in the $500-$750 range. Even more elaborate oscilloscopes are available from both companies but require considerable engineering sophistication in their operation if they are to be fully utilized.

For the small shop the TV oscilliscope kits sold by Allied or Heath represent a good buy. They are not provided with DC amplifiers or triggered sweeps but are wideband scopes with a response from about 5 cycles to 5 megacycles. We feel that if the investigator has a minimal amount of ability with a soldering iron and some ability to follow a circuit diagram these kits represent a good oscilloscope buy. They are to be preferred over the wired scopes in the lower price ranges.

10.11. ***Summary.*** The laboratory shop should include at least a multimeter, a vacuum tube voltmeter and an oscilloscope. In addition, a frequency standard such as an oscillator (discussed in Chapter 6) or a time interval meter (discussed in Chapter 7) should be included. These are the basic instruments. They can be supplemented by a standard DC voltmeter and a thermocouple AC meter for reference measurements. A 20 microampere meter, a 50-0-50 zero center galvanometer and an 0-1 milliampere meter should be added especially if transistor work is to be attempted. Current meters are essential to transistor work.

We have found that for the small shop the various kits supplied by Allied Radio or by Heathkit are excellent values. The average time of construction is about 8 hours for the skilled technician and about 16 hours for relatively unskilled workers. They are almost foolproof. As with any instrument the results depend largely upon how carefully the instrument is assembled. All kits are supplied with detailed instructions for assembly and calibration.

Chapter 11

TRANSISTOR THEORY AND APPLICATION

11.1. ***Applications.*** Probably no other electronic device in this century has enjoyed such rapid development and expansion of use as has the transistor. First demonstrated to the public in 1948 as a laboratory curiosity, the basic transistor types have multiplied from only one to nearly fifteen. Several dozen manufacturers are in commercial production of an average of ten or more variations of these general types. The next decade will probably see the obsolescence of many vacuum tubes and their replacement by transistors in circuitry used for radio, TV, military and instrumentation uses.

Military demands for electronic instrumentation led to a miniaturization of components since such useage demands compactness, freedom from shock damage, operation under the extremes of environmental factors, reliability and long life. These are almost precisely the advantages offered by transistors. While tubes will still outperform transistors in many applications, continuing improvement in transistors will eventually produce types which will prove superior to tubes in most applications.

While the transistor is an amplifying device similar in function to the triode tube, its operation is basically quite different. It will be necessary therefore to review briefly some theory and principles of transistor operation.

11.2. ***Transistor Theory.*** Transistors are made from comparatively rare metals called semi-conductors; germanium, selenium or silicon. These are crystalline elements which behave electrically somewhere between insulators like glass and conductors such as copper. In order to insure proper characteristics the metals are first highly purified by special processes and then deliberately contaminated with minute amounts of materials like arsenic, phosphorus, boron, gallium and aluminum.

In this impure form current flow is expedited by two different methods. When germanium is treated with metals of the arsenic group which have one electron in the outer ring in excess of that possessed by germanium, the resultant is termed "N" type germanium. Current flow in "N" type germanium is maintained by the passage of free electrons just as in an ordinary conductor. When an impurity of the boron type is added, with one electron less than germanium in the outer ring, it is called "P" type germanium and current flow takes place by the passage of "holes." These holes are somewhat figurative and occur as the result of the capture by an impurity molecule of an electron from an adjacent germanium molecule. Thus robbed, it in turn captures an electron from a neighboring molecule. Thus, figuratively, current flow in P type germanium may be considered a migration of positively charged particles.

If a slice of N type is placed in intimate contact with a slice of P type, and electrodes are connected to their outer extremities, an attempt to pass current from a battery through the resulting junction will produce very peculiar results.

If the negative pole of the battery is connected to the N slice and the positive pole to the P slice, electrons in the N section will be repelled towards the junction while the holes in the P slice will also be repelled towards the junction. At the junction there is a free exchange of holes and electrons and consequently, a current flow in the circuit.

If the above situation is reversed so that the negative pole is connected to the P slice and the positive to the N slice, free electrons will be attracted to the positive pole and holes will flow toward the negative pole. Very few electrons or holes will remain at the junction. The system is stalled and there is therefore little current flow. The germanium behaves like a very high resistance.

When an alternating current is connected to this arrangement it will be seen that conduction will occur only on alternate half cycles just as in the diode rectifier. Semiconductor rectification was first used in the detection of radio waves. Lead sulphide crystals and "catwhiskers" were used. Germanium and silicon diodes are commercially available in many different types. The 1N34 is a representative type.

11.3. ***NPN and PNP Junctions.*** The transitor consists of three slices of germanium or silicon as shown in Figure 3.1. A lead is connected to each slice of the sandwich and are termed respectively, emitter, base and collector. The reason for these terms will become apparent upon examination of the junction transistor.

Two batteries are now required. The base electrode is common to both batteries. If the polarity in Figure 3.1 is examined, it will be seen that the left half, the emitter diode, is biased in a forward direction so that it exhibits a low resistance and electrons are injected into the base region. The collector diode or right half is biased in a reverse direction causing current flow to be near zero and the diode to appear as a high resistance. The electrons pass freely from emitter to base and some combine with holes in the base layer. The majority, however, continue through the base-collector junction and return to the source.

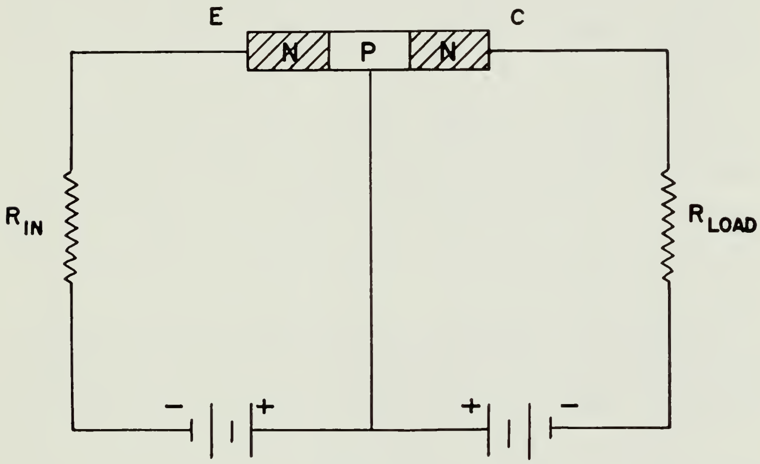


Fig. 11.1

If a signal is applied which makes the base more negative with respect to the emitter, the flow of electrons will be impeded. If the signal is so polarized as to make the base less negative (more positive) with respect to the emitter the flow will be enhanced. The base region therefore serves a function analogous to the grid of a triode tube; the emitter is analogous to the cathode and the collector is analogous to the plate. Small changes in the base input current will produce large changes in the collector current flow.

Efficiency is less than 100%. Not all the injected electrons reach the collector since some always combine with holes in the base to produce neutral atoms. The ratio of collector change to emitter current change is therefore less than 1 in the junction transistor. This ratio is called "alpha" and is comparable to the term mu as it is used to describe tube gains. Because of the low input and high output impedances of the transistor, considerable power gains are possible. It is also apparent that while tubes amplify voltage changes, transistors amplify current changes.

11.4. ***Other Transistor Types.*** The transistor just described was of the NPN type. PNP types are made by a different arrangement of germanium slices and operate in an identical fashion except that the polarity of the batteries must be reversed. Conduction is accomplished by holes, not electrons.

Point-contact transistors differ from the arrangement shown above. A tiny block of either P or N type germanium forms the base. The collector and emitter are tiny wire "catwhiskers" held in intimate contact with it. The assembled unit is "formed" electrically so that small areas of the opposite type germanium is created directly beneath the collector and emitter electrodes. The current gain of the point-contact transistor is greater than 1, a phenomenon attributed to the forming of both P and N types directly underneath the electrodes, creating in effect a tandem of two transistors. Point contact transistors are infrequently used except for high frequency applications where their performance exceeds the junction type, presumably due to the greater proximity of the emitter and collector with consequent lowering of the transit time of the electrons and holes.

The "coaxial" type is a variation of the point-contact type with the collector and emitter wires at opposite ends of the germanium base slice.

The "surface-barrier" transistor is produced by electrically etching the germanium slab to extreme thinness with the emitter and collector wires on opposite sides of the slice.

The "intrinsic-region" transistor has a PNIP construction with the I region being composed of a thin slice of pure germanium which increases the collector back resistance and may permit operation up to kilo-megacycles.

The "hook" transistor is a PNPN formation which is in effect a transistor within a transistor and provides more gain than the conventional junction type.

The "field-effect" transistor is a complete innovation with terminals called "source," "gate," and "drain." These terms replace the familiar emitter, collector and base. This type displays such increased input and output impedances that it may be substituted directly for a tube. This is not possible with other transistors.

The "tetrode" transistor has diametrically opposed base terminals serving somewhat the same function as the control and screen grids in the vacuum tube. Charges on these bases squeeze out conduction.

The "tandem" transistor is two transistors interconnected within the same envelope, while the dual transistor is merely two non-connected transistors in the same envelope.

Photodiodes and phototransistors are presently available but are not pure types. They utilize the electron-hole dissociative effects of light upon the germanium to produce photoemissive effects.

Junction transistors are the most useful for instrumentation purposes. The manufacturer's literature usually lists the characteristics of each type. At this time there is no comprehensive catalogue of characteristics of transistors comparable to the RCA or Sylvania tube handbooks. Most junction transistors are designated "CK" or "2N" which identifies RETMA registered types. The most useful types for simple circuitry are the CK721, CK722, 2N104, 2N107, 2N170, 2N34, 2N35, 2N68, 2N95 and 2N109. The types 2N68 and 2N95 are 2.5 watt PNP and NPN power transistors. The 2N109 is a low noise type. The 2N104 is a high gain low noise unit which is relatively stable with respect to temperature changes.

11.5. ***Electrical Characteristics.*** Transistor literature will include various electrical characteristics; whether NPN or PNP, collector voltage, emitter current, current amplification factor, power gain and input and output impedances. The term "cut-off current" refers to the collector current drawn with the base disconnected (no signal) and potential applied between the emitter and collector. The term "frequency cut-off" applies to the frequency at which the power output has dropped to one half its value at 1000 cycles. This is a 3 db drop in power output.

11.6. ***Transistor Amplifier Configurations.*** Any of the three elements of a transistor may be used as an input. One of the remaining terminals is made common to the other two and this is used to designate the type of amplifier. Three possible configurations with their vacuum tube analogs are shown in Figure 11.2. The input and output impedances of these amplifiers are very similar to their vacuum tube prototypes. The common emitter is perhaps most often employed as a DC amplifier.

11.7. ***Contrasts Between Tube and Transistor.*** One of the most striking features of the transistor is the relative lack of isolation between input and output circuits. The transistor is a four terminal active resistance network in which the load affects the input parameters and vice versa. This is most apparent in multistage direct coupled amplifiers. Transformer coupling provides a measure of isolation.

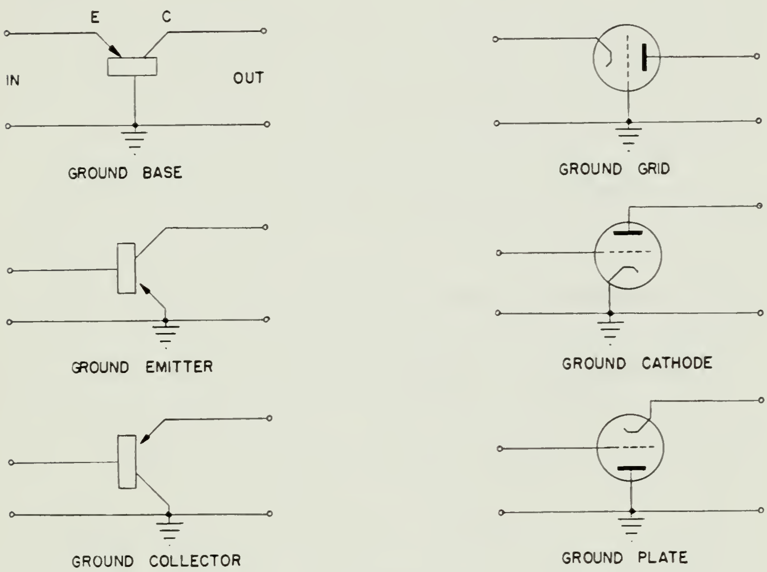


FIG. 11.2

Another important difference is that the transistor is a current amplifier while the tube is a voltage amplifier. Both voltage and power gains are attainable in transistor circuits, however.

Transistors are also heat sensitive. Heating a unit will greatly increase the current flow and may cause the transistor to become damaged. In fact, exceeding the current rating of a transistor will cause its internal temperature to rise. It becomes a better conductor, the current flow and consequently the heat generated rises and the transistor may destroy itself by this means. Power transistors are usually connected to a large metal area or "heat sink" to provide adequate dissipation of heat.

Power requirements of transistor circuitry are low. In conventional vacuum tube circuitry considerable power is consumed in heating the filaments. Since the transistor does not require filamentary heating this power is saved. Plate potentials seldom exceed 25 volts in transistor circuits. Exceptional performance in many circuits may be obtained with polarizing potentials as low as 1 volt.

11.8. ***Representative Transistor Circuits.*** The following circuits have been selected to demonstrate the general utility of transistors or to demonstrate a type of application. Modifications may be made in the basic circuits provided the manufacturer's ratings are not exceeded.

11.9. ***Transistor Trigger.*** This circuit uses a moderately priced relay and transistor to provide high-sensitivity relay action. The circuit is illustrated in Figure 11.3.

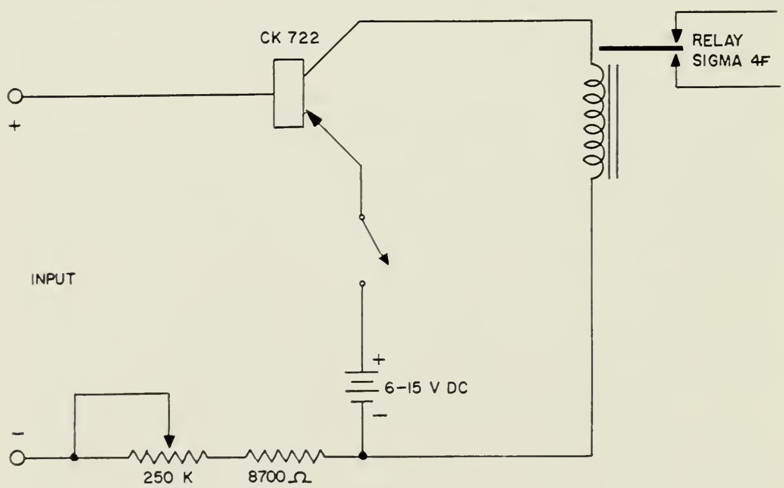


Fig. 11.3

Operation is as follows: With no signal on the base the current through the relay is limited to a few microamperes. When either a potential or a resistance is applied between emitter and base the collector passes current in proportion to the signal impressed. Resistor R_2 provides a control over the sensitivity.

A photovoltaic selenium cell may be attached to the input to provide photoelectric control of operation. The circuit may be used in timing applications, since a very brief or weak input current will produce relay operation. A cadmium sulfide cell and a source of potential may be connected to the input to provide an accurate, low-level light meter.

11.10. ***Pushpull Amplifier.*** The circuit shown in Figure 11.4 illustrates an application borrowed from vacuum tube circuitry. It is quite stable due to the use of the RCA

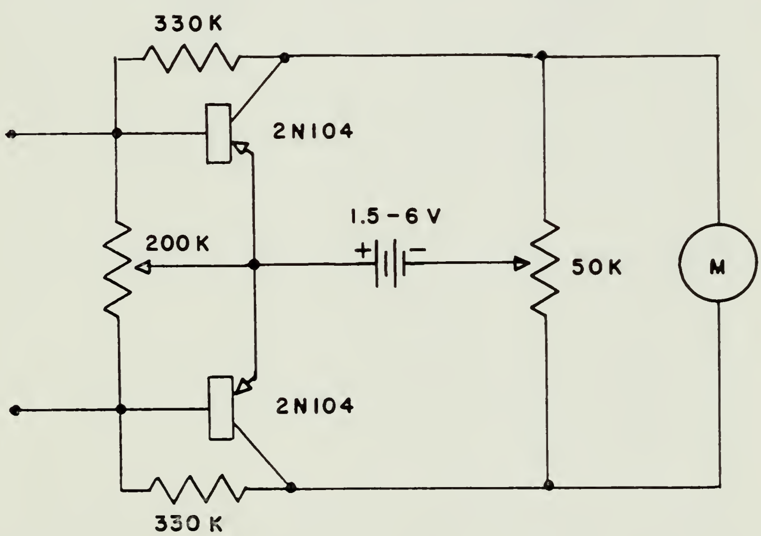


Fig. 11.4

2N104 transistor. While the circuit is a high-gain circuit, the gain can be increased by substituting a Texas Instrument 2N185 transistor. It has been used in our laboratory to amplify the output from a PGR bridge. When used with a 50 microampere meter it will give full scale deflection for 10% changes.

Changing the feedback resistors R_1 and R_2 will change the sensitivity. R_3 is used for a meter zero set with no input signal. Mercury cells are used for power. Any voltage from 1.345 to 15 volts may be used.

11.11. ***Cascaded Amplifiers.*** Transistors may be cascaded for additional gain. The circuit shown in Figure 11.5 will provide more than 60 db gain with low-priced tran-

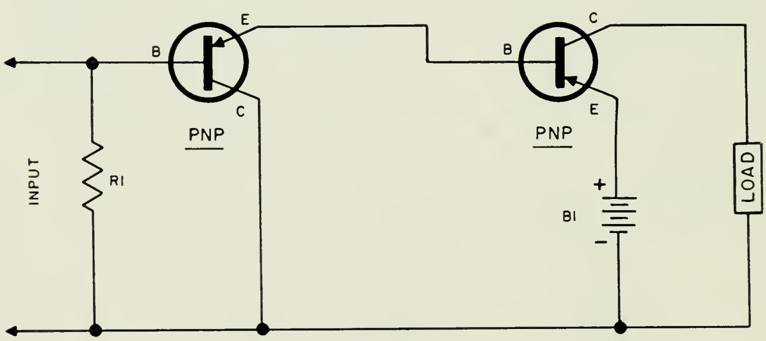


Fig. 11.5

sistors. With either the degenerative feedback shown or with thermistor meter shunts this circuit is very useful for biological work.

11.12. ***Transistor Timer.*** This extremely simple circuit utilizes RC principles in combination with a relay.

It is shown in Figure 11.6. When Switch 1 is thrown momentarily toward A, the 50 mfd condenser is charged. To operate, the switch is thrown to position B. At this time the base is strongly biased in a positive direction and current flows through the relay, closing it. The condenser is discharging through R_2 and after a time delay set by the value of R_2 the bias falls to a point where the collector current is no longer able to hold the relay closed. This terminates the timed cycle.

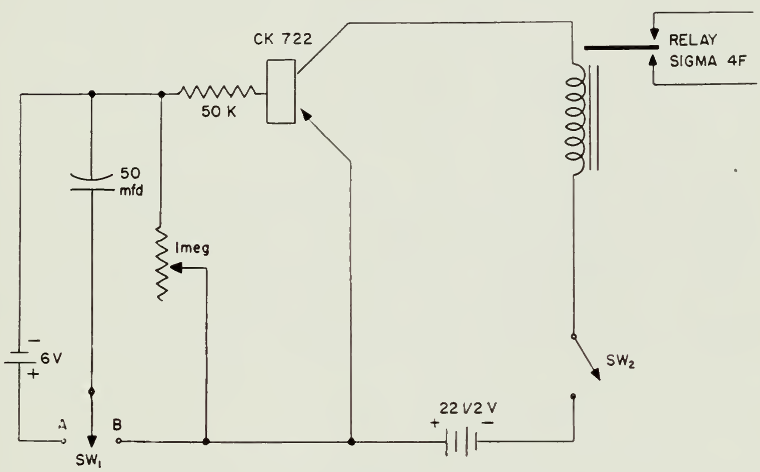


FIG. 11.6

The device may be made to recycle by using a DPDT relay so that the condenser is immediately returned to Point A. The entire cycle will then be repeated because as soon as the relay arm touches point A the condenser is recharged and the relay closes, making contact at point B.

11.13. ***Transistor Multivibrator.*** The circuit illustrated in Figure 11.7 is quite similar to vacuum tube multivibrators. It is an RC coupled amplifier with feedback supplied by the capacitor C_x. The output waveform is square and may be varied from 235 pulses per second with 0.01 mfd at C_x to 2000 pulses per second with 0.0005 at C_x. An input of 5 volts rms at the Synch In terminals will cause the multivibrator to lock in synchrony at as much as 10 times the base frequency. As with the tube circuit, this device may be used to count down pulses for timing operations.

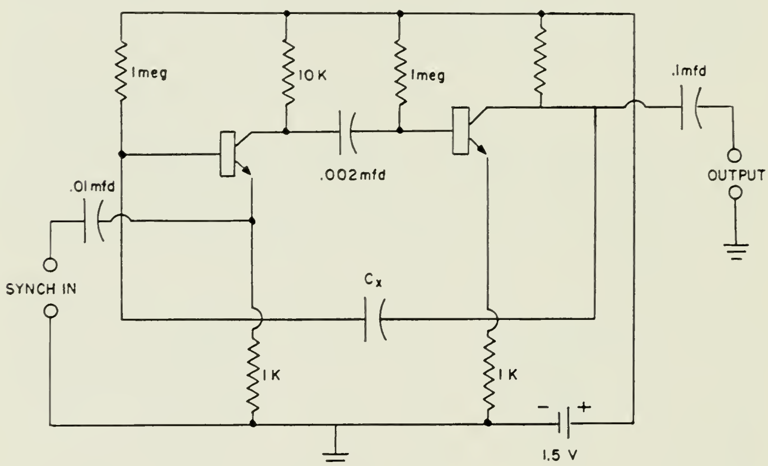


FIG. 11.7

11.14. ***Transistor Oscillators.*** For the generation of auditory stimuli the circuit shown in Figure 11.8 provides a pulse output variable in frequency from 200 cycles per second to 10KC per second. Since the emitter and collector of a transistor have a common coupling in the base, only a slight amount of additional impedance is needed in the base arm to sustain oscillations. This is provided by the primary of an ordinary output transformer in the circuit shown. This feeds an in-phase signal back to the base. Note that the transistor is a point contact type with an alpha of 2.2. Pitch can be varied by the 5K potentiometer.

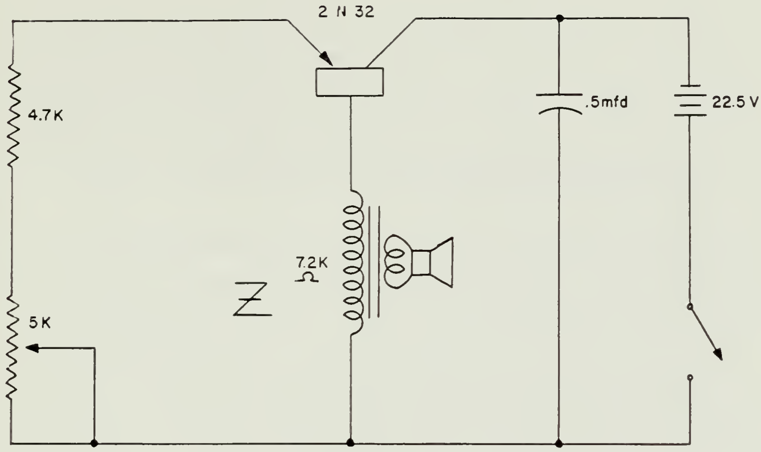


FIG. 11.8

11.15. ***Cortical Stimulator.*** In the circuit in Figure 11.9 an RC network has been substituted for the LC circuit shown in Figure 11.8. It is now possible to obtain spike wave output formations variable in frequency from 5 to 100 cycles per second and from 2 to 20 volts in amplitude.

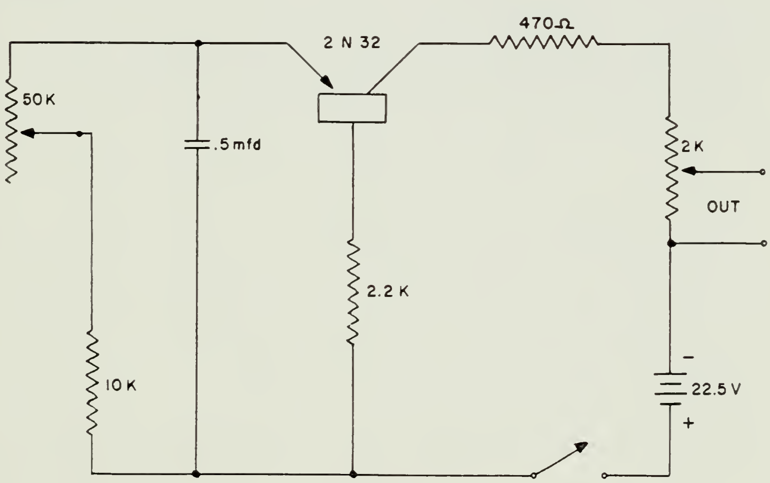


FIG. 11.9

11.16. ***Audio Amplifiers.*** Extremely small high gain audio amplifiers can be built with transistors. These can deliver up to 5 watts of audio power. At the present time most transistor audio amplifiers are transformer coupled due to difficulty in matching input and output impedances with RC coupled amplifiers.

Special transformers must be used, since the impedances are quite low, especially with power transistors. Some may have input impedances on the order of 50-100 ohms.

The final stages are usually push-pull, using either NPN transistors such as the Sylvania 2N68 or PNP transistors such as the Sylvania 2N95 in matched pair or complementary circuits. It is imperative that power transistors be attached to a metal heat sink if they are to be operated at maximum ratings. Otherwise they must be heavily de-rated. The major design advantage is that such transistors are able to deliver 5 watts or more of audio power into a speaker or other low impedance device with a 6 volt or 12 volt source.

We feel that in time the high power output and low supply voltage requirements will lead to the development of transistorized driver circuits for recording pens and other recording devices useful in behavioral research.

Chapter 12

THE LABORATORY WORKSHOP

12.1. ***Introduction.*** Many research laboratories have grown in a purely random fashion. It is altogether too infrequent that research personnel and architects have planned laboratory space for new construction. Space is usually at a premium and when offices, testing rooms and storage are taken out of available footage, there is little room left for shop facilities. Yet it is the contention of the authors that some instrument shop facilities are necessary for the operation of a research laboratory.

Such a shop may well be of modest dimensions, suitable for one full-time person and an occasional helper. While the actual layout will vary greatly with the amount of space available, certain requisite minimum equipment and supplies will be required and will be discussed beneath.

12.2. ***Power Tools.*** Since almost all new electronic construction and modification work begins with machining operations, the following tools are considered to be basic equipment for the instrument shop.

1. ***Drill Press.*** This should be an inexpensive bench type tool capable of handling work up to 18 inches tall. A drill press of this type is available from Sears. The drill chuck should accept bits up to ½ inch in diameter and there should be some provision for changing drill speed, either by cone pulleys, or preferably, by some variable speed device such as that available as an accessory on the Sears drill-press. The motor should be of appropriate

voltage rating and either a quarter or half-horsepower. A foot switch should be used for operation since this allows both of operators hands to be freed. A complete set of high speed steel drills should be provided in number sizes from #60 to #1, and in fractional sizes from ¼ to ½ inch in 1/64 inch steps. While not absolutely necessary, an additional set of letter drills from size A thru Z is very useful.

Essential accessories include; a drill press vise, center drill set, an adjustable "hole cutter" for large diameter openings up to 2 inches in diameter, and either tool-makers' or "C" clamps for holding large work to the drill press bed. Machine type reamers should be available in 1/4, 3/16, 3/8 and 1/2 inch and there should be several 1/4 inch straight shank end mills for working soft metals and plastics. The drill press should be firmly bolted to a stand or table.

2. ***Additional Power Tools.*** A lathe, bandsaw, belt and disc sander and bench grinder are quite useful in general instrument construction but are not absolutely necessary for all electronic work. A convenient size of bandsaw is that using 80 inch circumference blades. Blades may be purchased which will cut non-ferrous and ferrous materials. If a lathe is to be purchased, it is suggested that the cheaper types be avoided. It is better to buy a rebuilt or used tool-makers lathe. Suggested size of lathe for laboratory work is probably one with an 8 inch swing and approximately 30 inch between centers. Both three and four-jawed chucks should be purchased.

12.3. *Miscellaneous Mechanical Tools.* The following small hand tools should be provided; a complete set of insulated handle screwdrivers, small machinists' hammers and sheet metal hammers, at least one large mechanics' vise and one small vise, a collection of pliers including gas-pipe pliers, small and large diagonal wire cutters, needle-nose pliers, "bent" pliers, round-nose pliers, 6 and 8 inch adjustable wrenches, a set of small socket wrenches, a set of "Spintite" wrenches, sets of Allen and spline wrenches, a set of jewelers' screwdrivers, sheet metal scribers, a surface gage, 1 inch micrometers, a set of taps and dies from 4-36 to 3/8-24, large tweezers, tin shears, a set of chassis punches from 1/2 to 1 15/32 inches, a tapered hand reamer and a hacksaw for metal cutting. With few exceptions, all of the above may be purchased from a mail-order house such as Allied Radio.

12.4. ***Miscellaneous Electrical Tools.*** The requisite electronic shop equipment has been discussed in Chapter 10. Small tools required in addition include; several 100 watt soldering irons, small "pencil" type irons such as those made by Ungar, wire strippers, and several pound spools of 1/16 inch diameter 60-40 solder.

12.5. ***Component Stocks.*** Component stocks should be maintained at fixed levels which are best determined after the shop is in operation. It will be of great assistance to the technician to have readily available stocks of tubes, sockets, chassis, resistors, capacitors, transformers and connectors. A list of the most frequently used varieties of tubes will be found in the Appendix. While variable resistors (potentiometers) are available in a variety of tapers, a term used to describe the slope of the curve plotted from amount of resistance versus degrees of shaft rotation, a linear taper potentiometer can be used for most applications.

Stocks of electronic hardware should include the following items: machine screws, preferably nickel-plated in 6-32 size and ¼, ½ and 1½ inch lengths, 6-32 hex nuts, rubber hole grommets in several sizes, soldering lugs, terminal strips, phone jacks and plugs, pilot light lamps and sockets, "L" brackets, lock washers, tube sockets in octal, miniature nine and miniature seven pin sizes, banana plugs and sockets, multiple connectors such as the Jones or Amphenol line, knobs, dials and AC line cords. It should be noted that such items are most economically purchased in gross lots.

The varieties of wire and cable to be carried in stock may be reduced to the following: #22 solid wire with thermoplastic cover in five colors, #14 bare tinned wire, shielded single conductor cable (sold as grid wire), and 50 foot lengths of both five and ten conductor cable, and several hundred feet of both red and black rubber covered test lead cable of the "limp" variety.

12.6. ***Test Construction.*** Unless one has had considerable experience in designing and building circuits, it is not good practice to construct a new circuit on the final chassis or cabinet. Such practice leads to the waste of components since even the best of engineering designs may not perform without alterations. It is therefore important to begin the construction of a new circuit on a temporary chassis known as a "bread-board." While commercial models are available, the authors have found a 6x18 inch sheet of heavy guage aluminum mounted on 5 inch legs to be as useful. The sheet should be punched for 4-6 octal sockets and an equal number of 7 and 9 pin miniature sockets. The sockets should be mounted with their terminals upwards and terminal strips should be mounted close by. If a number of 3/8 inch holes are provided in the plate, potentiometers may be mounted with their shafts downwards. New circuits may be quickly wired since all terminals are upwards.

A variable power supply should be used to provide the required voltages and an oscilloscope, VTVM or bank of suitable meters may be employed to read input and output signals. A circuit so constructed may be quickly optimized and the final instrument built from these values.

12.7. *Chassis Layout.* Once the optimum circuit values have been determined on the bread-board and the circuit recorded, the final chassis layout should be made. Aluminum chassis are preferable to steel since they are more easily machined. Most chassis come completely wrapped in brown paper. This may be used as a surface on which to make componet layouts. A good practice is that of placing the actual components, transformers, tube sockets, etc., on the top surface to determine if adequate space is available for wiring, placement of controls and meters, cabinet clearance and ventilation. While the actual layout is left to the ingenuity of the constructor, some general principles may be enumerated:

1. Sub-units should be located in groups. For example, the power transformer, filter choke, condensers, rectifier and voltage regulator tubes make up the power supply unit and should be mounted together.

2. Octal sockets should not be mounted closer than 2½ inches center-to-center. Tube sockets are best mounted in rows, front-to-back rows for a unit, with units side to side of the long dimension of the chassis.

3. Controls such as switches and potentiometers are best mounted on the panel in the lower portion where the terminals will be accessible inside the chassis. Where this is not possible, rubber-grommeted holes should be provided in the chassis.

4. Switches and controls should be mounted so that their "up" position is "on," or with rotary controls, so that clockwise rotation is "on" or "increase." Meters usually have a left-hand zero, therefore any control which will affect meter settings should be wired so that knob rotation and meter deflection are in the same direction.

5. Use all chassis space but allow for the mounting of at least one additional control, switch or tube to take care of possible circuit alterations.

12.8. ***Wiring.*** Observe the following procedure in the actual wiring: Make each lead as short and direct as possible. Keep all wiring as close to the chassis as possible. Wiring, except for high-frequency circuits, should be laid out so as to consist of straight lines with right angle bends, since this permits circuit tracing to be performed with greater ease. Use colored wires, coding the circuit red for B plus, black for B minus, yellow for filaments and green for grid leads. Keep input and output circuits isolated from each other, particularly in high gain amplifiers. Bend and mechanically secure all wires to terminals before soldering. Use a hot iron, thin 60-40 solder of the rosin core variety. *Never use acid core solder, paste or flux.*

When finished wiring a circuit, trace it visually before applying power. Check the operation of the power supply first with the remaining tubes removed.

Appendix I

REFERENCES

1. Berkley, E. C.: *Giant Brains*. Wiley Radio and Electronics Publications.
2. Cooke, N. M.: *Mathematics for Electricians and Radiomen*. New York, McGraw-Hill.
3. Cooke, N. W. and Marcus, N.: *Electronics Dictionary*. New York, McGraw-Hill.
4. Cooke, N. M. (ed.) : *Allied's Electronics Data Handbook*. Allied Radio Publications.
5. Dickenson, C. J.: *Electrophysiological Technique*. London, Electronic Engineering, 1950.
6. Electronics Master: (*Radio's Master*.) United Catalog Publisher (published annually) .
7. Crufts Electronics Staff: *Electronic Cricuits and Tubes*. New York, McGraw-Hill, 1947.
8. Keister, A. E., Ritchie, S. H., and Washburn, J.: *The Design of Switching Circuits*. Van Nostrand.
9. Maedel, G. F.: *Basic Mathematics for Television and Radio*. Prentice-Hall.
10. Read, O.: *Recording and Reproduction of Sound*. Howard W. Sams Radio-TV Service Publications.
11. *RCA Tube Manual*, RC-17. (Published annually) .

12. John F. Rider Publications: Van Valkenburgh, Nooger and Neville: *Basic Electronics.* Van Valkenburgh, Nooger and Neville: *Basic Synchros and Servomechanisms.* Rider, J. F., and Uslan, S.D.: *Encyclopedia on Cathode-Ray Oscilloscopes and Their Uses.* Krugman, L.: *Fundamentals of Transistors.* Rider, J. F.: *How to Use Meters.* Rider, J. F.: *Obtaining and Interpreting Test Scope Traces.*

13. Samuel, R.: *The VTVM.* The Gernsback Library.

14. Shea, R. F.: *Principles of Transistor Circuits.* Wiley Radio and Electronics Publications.

15. Lo, Endres, Zawels, Waldhauer and Cheng: *Transistor Electronics.* Prentice-Hall.

16. Trimmer, J. D.: *Response of Physicial Systems.* New York, Wiley, 1950.

17. Whitfield, I. O.: *Introduction to Electronics for Physiological Workers.* London, MacMillan, 1953.

18. Federal Telephone and Radio Corporation: *Reference Data for Radio Engineers.* 3rd Ed., 1949.

19. Publications Available From Supt. of Documents, U. S. Government Printing Office, Wash. D. C.

    1. *Basic Electronics,* 1955, 728 p., Il., $2.25, Cat. D-208. 11-E12/10/1955.

    2. *Basic Theory and Application of Electron Tubes,* 215 p., Il., $1.00, Cat. D-101.11:11-662.

    3. *Cathode Ray Tubes and Their Associated Circuits,* 1951, 218 p., Il., $1.00, Cat. D-101.11:11-671.

    4. *Handbook, Preferred Circuits, Navy Aeronautics Electronic Equipment,* 1956, 202 p., Il., $1.75, Cat. D-202.6:C49.

5. *Introduction to Electronics,* 1949, 40 p., Il., $0.35, Cat. M-101.18:11-660.

6. *Physics of Electronics Technicians,* 1951, 378 p., Il., $1.25, Cat. D-208.11:p56.

7. *Pulse Techniques,* 1951, 102 p., Il., $0.50, Cat. D-101.11:11-672.

8. *Radar Circuit Analysis—Air Force Manual 52-8,* 1951, 480 p., Il., $2.25, Cat. D-301.7:52-8.

9. *Radar Electronic Fundamentals,* 1947, 474 p., Il., $1.25, Cat. 29.2:R11/3.

10. *Servo Systems and Data Transmission,* 1952, 117 p., Il., $0.60, Cat. D-101.11:11-674.

11. *Theory and Use of Electronic Test Equipment,* 1952, 158 p., Il., $0.75, Cat. D-101.11:11-664.

12. *Timing Circuits, Naval Trng. School, MIT,* 1951, 68 p., Il., $0.30, Cat. N29.2:C49.

Appendix II

SELECTED PERIODICALS

1. Electronics, McGraw-Hill.
2. Journal of Scientific Instruments, The Institute of Physics, London.
3. Radio and TV News, Ziff-Davis Pub. Co., N. Y.
4. Radio Electronics, Gernsback Pub. Inc., N. Y.

Appendix III

COMMERCIAL SOURCES OF INSTRUMENTS AND COMPONENTS

1. Advance Electric and Relay Co., 2435 North Naomi St., Burbank, Calif., (Relays) .
2. Allied Radio Corp., 100 N. Western Ave., Chicago 80, Ill., (Components, kits, instruments, etc.) .
3. Amglo Corporation, 2037 W. Division St., Chicago 22, Ill., (Flashtubes).
4. Brush Electronics Co., 3405 Perkins Ave., Cleveland 14, Ohio, (Amplifiers, Mikes, Penwriters) .
5. Baldwin-Lima-Hamilton Corp., Philadelphia 42, Pa., (Wire strain gages) .
6. Esterline-Angus Co., Indianapolis, Ind., (Recording Milliammeters, Event Markers) .
7. Edmund Scientific Corp., Barrington, N. J., (Optical Surplus) .
8. Edin Co., Inc., 207 Main St., Worcester, Mass., (Pen motors, recorders) .
9. Friez Instrument Division, Bendix Aviation Corp., Baltimore 4, Md., (Thermistors) .
10. General Radio Co., Cambridge 39, Mass., (Oscillators, Amplifiers, Instruments) .
11. G. M. Giannini and Co., 918 East Green St., Pasadena 1, Calif., (Small, low torque potentiometers).

12. Helipot Corp., (Division Beckman Instruments), South Pasadena, Calif., (Precision potentiometers).

13. Hewlett-Packard Co., Palo Alto, Calif., (Oscillators, oscilloscopes).

14. Heathkit Corporation, Benton Harbor, Mich., (Instrument kits).

15. Hupp Electronics Co., 743 Circle Ave., Forest Park, Ill., (Cadmium Sulfide Photocells).

16. Heiland Research Corp., 130 East 5th Ave., Denver 9, Colorado, (Recorders).

17. Haydon Mfg. Co., Inc., Torrington, Conn., (Small timing motors).

18. International Rectifier Corporation, 1521 E. Grand Ave., El Segundo, Calif., (Selenium photocells).

19. Potter and Brumfield, Princeton, Indiana, (Relays).

20. Phipps and Bird Co., 6th and Byrd Sts., Richmond 5, Va., (Instruments).

21. Radio Corporation of America, (RCA), Tube Dept., Camden, N. J., (Tubes, equipment, transistors).

22. Raytheon Mfg. Co., 55 Chapel St., Newton 58, Mass., (Tubes, Transistors).

23. Radio Shack Corporation, 167 Washington St., Boston 8, Mass., (Components, Equipment).

24. Sylvania Electric Products, Inc., 1740 Broadway, New York 19, N. Y., (Tubes, Transistors).

25. Sigma Instruments, Inc., 170 Pearl St., Braintree, Boston 85, Mass., (Relays).

26. Stancor (Chicago Standard Transformer Co.) Addison St. and Elston Ave., Chicago 18, Ill., (Transformers).

27. Sola Electric Co., Chicago 50, Ill., (Constant Voltage Transformers).

28. Statham Labs, Inc., 12401 W. Olympic Blvd., Los Angeles 64, Calif., (Pressure Transducers).

29. Sears Roebuck (locally), (Shop Tools).

30. Tektronix, P. O. Box 831, Portland 7. Oregon, (Scopes, Timing Circuits).

31. Thordarson-Meissner, 7th and Belmont, Mt. Carmel, Ill., (Transformers, Coils).

32. United Transformer Co. (UTC), 150 Varick St., New York 13, N. Y., (Transformers).

33. U. S. Engineering Co., 521 Commercial St., Glendale 3, Calif., (Electronic Hardware).

34. Victory Engineering Corp., Springfield Rd., Union, N. J., (Complete Stocks of Thermistors, Varistors).

35. Waters Corporation, 402 First Ave. N. W., Rochester, Minn., (Heart Rate Apparatus).

36. Westport Electric, 149 Lomita St., El Segundo, Calif., (Timing Circuits).

37. Yellow Springs Instrument Co., Yellow Springs, Ohio, (Instruments; heart rate, PGR, etc.).

Appendix IV

PREFERRED TUBE TYPES

1. ***Rectifiers:*** 5Y3, full wave 5V fils, directly heated medium current capacity. Octal socket required.

6AX5, full wave 6V, indirectly heated slow warmup medium current rectifier. Can be heated from 6.3 volt windings on transformer. Octal socket required.

6x4, 7 pin miniature 6AX5.

5U4GB, full wave 5V fils, directly heated high current rectifier. Octal socket required.

2. ***Diodes:*** 6H6, full wave 6.3V fils, indirectly heated with separate cathodes. Ordinarily used as a signal rectifier or clamp diode. Octal socket required.

6AL5, 7 pin miniature 6H6.

3. ***Triodes:*** 6BX7, medium mu twin triode, 6.3V fils with separate cathodes. This tube is a TV deflection amplifier which will handle 40 ma plate current per triode. It can be used in regulated power supplies as a pass tube. Octal socket required.

6SN7GT, GTA, GTB, medium mu twin triode, 6.3V with separate cathodes. Amplification factor of 20. This tube is widely used in TV circuitry and as a multivibrator and control tube. Octal socket required.

6CG7, 9 pin miniature tube identical with 6SN7.

12AU7, 9 pin miniature twin triode which can replace 6SN7 or 6CG7 for many applications. The tube envelope is somewhat shorter than the 6CG7.

6SL7, high mu twin triode, 6.3V fils, seperate cathodes. Used as RC amplifier, multivibrator and control tube. Amplification factor of 70. Octal socket required.

12AX7, 9 pin miniature high mu twin triode which is identical with 6SL7.

4. ***Pentodes:*** 6SJ7, sharp cutoff pentode, metal or glass envelope. 6.3V fils with amplification factor of 19 as a single triode. Used as an audio or general purpose RC amplifier. Gains as high as 263 as a pentode can be realized. Octal socket required.

6AU6, sharp cutoff pentode, 7 pin miniature. Somewhat similar to 6SJ7 in application except that voltage gains of 371 can be realized.

5. ***Beam Power Tubes:*** 6V6, 6V6GT, metal or glass beam power tube, 6.3V fils. Can be used as a gate tube. When used as Class A audio amplifier will work at power level of about 5 watts. Class AB_1 circuitry will give power level of 14 watts. Octal socket required.

6AQ5, 7 pin miniature 6V6.

6L6, metal or glass beam power tube. 6.3V fils. Widely used as audio and RF amplifiers because of high power output, sensitivity and freedom from distortion and harmonics. Will deliver 47 watts as Class AB_2 push-pull amplifier. Octal socket and adequate ventilation required.

6. ***Regulators, VR Type:*** OC3/VR 105, cold cathode voltage regulator. Will regulate 105 volts at 5 to 40 milliamperes. Octal socket required.

OB2, 7 pin miniature, cold cathode, 108 volts 5 to 30 milliamperes.

OD3/VR 150, cold cathode voltage regulator. Will regulate 150 volts at 5 to 40 milliamperes. Octal socket required.

OA2, 7 pin miniature cold cathode voltage regulator. Will regulate 150 volts at 5 to 30 milliamperes.

7. ***Multigrid Amplifiers:*** 6SA7, pentagrid converter, 6.3V fils. This tube is ordinarily used as a converter in superhetrodyne RF circuits but may also be used as a mixer, control tube or phantastron time base generator. Octal socket required.

6BE7, 7 pin miniature 6SA7. These tubes are characterized by a special grid structure which results in little change in cathode current as a result of a change in signal voltage.

8. ***Thyratrons:*** 2050, gas tetrode, 6.3V fils. This is a relay and control tube which can handle 100 milliamperes plate current. Requires octal socket.

2D21, 7 pin miniature 2050 relay control tube.

5696, 7 pin miniature tetrode thyratron with a fast de-ionization time suitable for high-speed switching. Used for relay control and computers.

These are common types which are preferred for new design. Since many of them are used in radio and TV circuits, they are available in most localities in the USA and in the British Empire. Duplicates of most of these tubes are produced by English companies such as Mullard, by Telefunken and by Philips on the Continent.

INDEX

Date Due
